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Technical Report

THIN-FILM EVAPORATION IN VAPOR-COMPRESSION STILLS

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THIN-FILM EVAPORATION IN VAPOR-COMPRESSION STILLS

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by

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ABSTRACT

A study is made to explore promising mechanisms of heat transfer which may be used to develop more efficient sea-water distillation units. As a basis of investigation, an extensive research survey of low-temperature-difference boiling heat transfer is briefly summarized, with the conclusion that with the present understanding of ebullition there is little prospect of achieving the desired heat transfer with active boiling. The metal-to-fluid superheat necessary to form a steam bubble with known types and sizes of nucleation sites prevents ebullition except with minimum temperature differences of 8 to 10°F between the temperature of the metal wall and the saturation temperature of the fluid.

The concept of evaporation from a very thin film without boiling is considered in detail, and two small experiments are reported. It is shown, both theoretically and experimentally, that very high evaporation rates can be obtained with the very thin film technique; methods of maintaining a thin film continuously in a practical vapor-compression still are considered. A single-tube experiment, in which methods of introducing feed water and checking probable scaling problems will be studied, is described as the next phase of this task.

CONTENTS

NOMENCLATURE

A	Area
c_p	Specific heat at constant pressure
C	Constant
D	Significant physical dimension; diameter of tube
G	Mass flow per unit area
H	Static water leg height
h	Film coefficient of heat transfer
h_f	Enthalpy of a liquid at saturation
h_{fg}	Enthalpy of a vapor
h_g	Enthalpy of evaporation
K	Thermal conductivity
N_{Nu}	Nussult's Number (hD/K)
N_{Pr}	Prandtl's Number $(c_p\mu/K)$
N_{Re}	Reynold's Number (DG/μ)
Q	Heat flow per unit time
t	Temperature
t_∞	Bulk temperature
U	Coefficient of overall heat transfer
V	Velocity
v	Specific volume
W	Weight (of steam or fluid)
X	Quality of steam
x	Linear dimension in direction of heat flow
δ	Effective boundary layer thickness; thin-film thickness
Δt	Temperature difference
θ_{sat}	Temperature difference, tube wall to saturation temperature of fluid
θ_{wo}	$t_w - t_\infty$ at incipience boiling
μ	Viscosity

<u>Subscripts</u>

b	Boiling
c	Condensation
e	Evaporating
f	Fluid
g	Vapor
rad	Radial
sat	Saturation at local pressure
w	Tube wall

OBJECTIVE

The purpose of this task was to investigate new aspects of heat transfer which may lead to the development of simpler and more efficient apparatus for distilling potable water from sea water. This report presents a research study and a theoretical and experimental investigation, advances the requirements for an improved distillation process, and outlines an experimental effort which will constitute the next phase of this task.

THE PROBLEM

The removal of solutes from true solutions is at best a costly process. The expenditure of heat energy in the form of fuel is usually high, and in the absence of known fuel, labor, capital, and equipment costs, no single determination of optimum design can be formulated. It is, however, possible to consider those aspects of the process which will directly affect costs and, from this, perhaps eventually develop the guideline for the design of a superior machine.

Boiling as such is not necessarily the most satisfactory embodiment of the evaporation process. Two other evaporation processes, each with at least one potential advantage, will be explored.

Demineralized water is, in general, not competitive when other water, even of poor, but acceptable, quality can be obtained. According to knowledgeable engineering economists, the total costs of demineralizing water must be reduced by a factor of 2 before a market for demineralized water can be developed in most of the poor water areas.

The United States Navy has a considerable requirement for potable water in areas where only sea water is available. The most common desalting device on board ships is the sea-water evaporator, usually using low-pressure steam bled from the propulsion system. The convenience and relative simplicity of such a system where steam is available has made its use desirable in spite of its relatively poor production rate when compared, for instance, with that of the vapor-compression still. A four-effect evaporator would be hard pressed to produce 50 pounds of distilled water per pound of fuel oil, while a vapor-compression still, a smaller and lighter machine, can produce 180 pounds of product per pound of fuel. The production rate of the evaporator can be increased by increasing the number of effects,

while improvement of the heat-transfer rate can reduce the size of the machine. Improving the evaporating and condensing heat-transfer coefficients of the vapor-compression still by reducing or eliminating the relatively thick boundary layer in favor of a thinner fluid film could materially increase the heat-transfer rates and could decrease the size of the still.

It is the possibility of substantially reducing the overall cost of demineralized water by increasing heat-transfer rates alone that dictates extensive consideration of the vapor-compression principle and the feasibility of establishing and maintaining a very thin film.

LIMITATION OF VAPOR-COMPRESSION CYCLE

To establish a basis for further discussion, the cycle of the typical vapor-compression distillation machine will be described in some detail. Referring to Figure 1, the basic components are the evaporator, the compressor, and the prime mover. In the latter, fuel is burned in an internal-combustion engine to produce shaft power. This power is used in a low-pressure compressor, usually of the positive-displacement type because of the pressure ratios necessary with currently used heat-transfer processes. In the compressor, the vapor (low-pressure steam) is raised in pressure, and hence in saturation temperature, and readmitted to the evaporator section outside the tubes, where it condenses. This increase in saturation temperature provides the driving force for the cycle, and the enthalpy necessary to obtain this temperature increase determines the efficiency of the cycle.

The heat required by the cycle for brine preheating, heat loss, etc., is readily available in the engine's exhaust and cooling jacket. The heat from the exhaust gas is usually recovered in a simple, relatively inefficient boiler, and that from the engine itself by boiling water in the engine-cooling jackets. The steam thus produced is condensed at the point of use, and the condensate is returned to the engine and to the exhaust boiler in a closed cycle.

Figure 2 shows a temperature-entropy diagram of the vapor-compression cycle. Point values of enthalpy are those for distilled water; possible small effects of salt content on heat capacity and vapor pressures in the actual machine are neglected. The condensing (saturation) temperature and pressure are represented on the upper horizontal line; the lower horizontal line represents the boiling at low pressure conditions. The vapor is compressed along some line A-B to the higher, or condensing, temperature and pressure, and change in enthalpy in the compressor along A-B represents the heat input necessary to produce a pound of water.

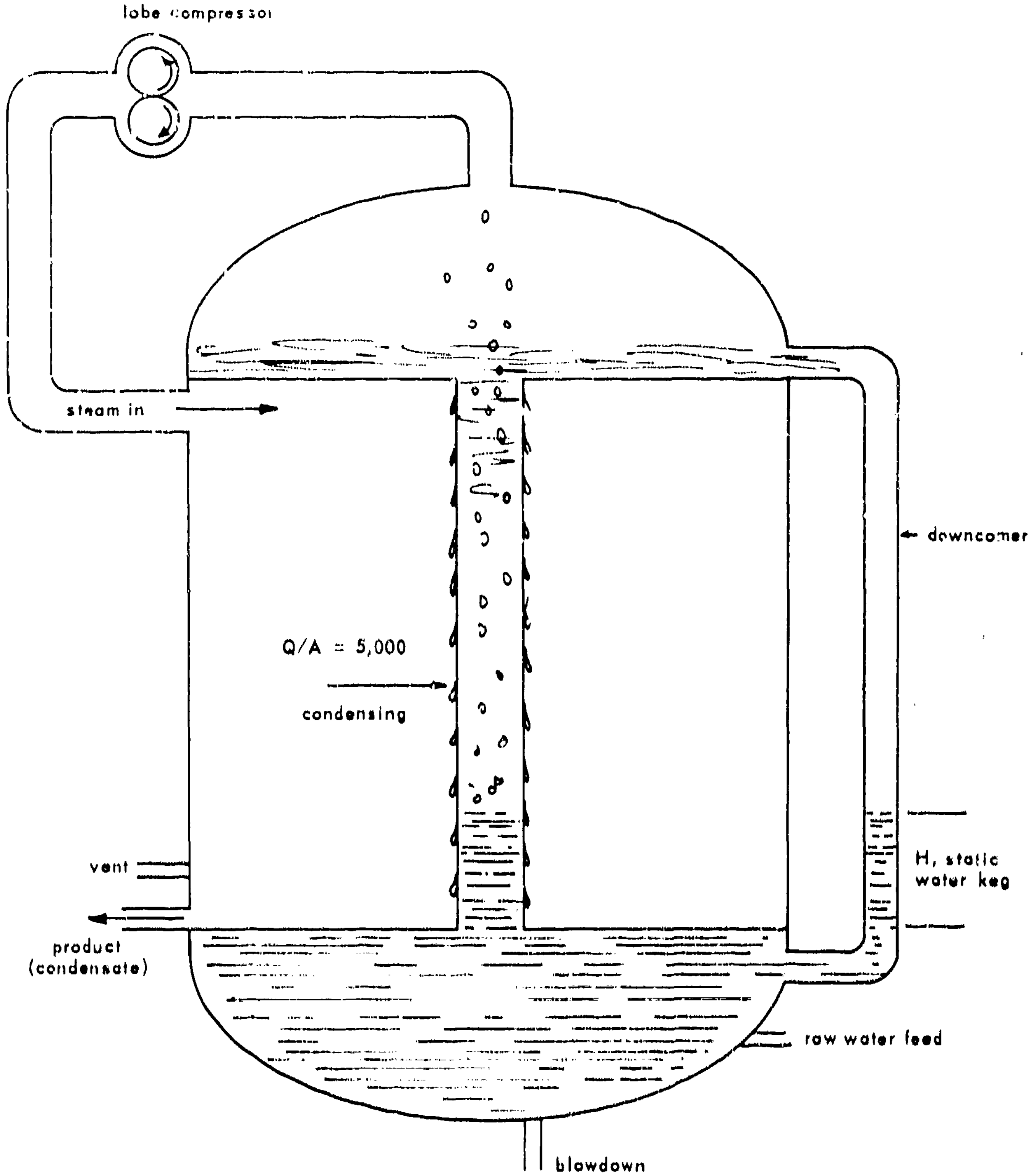

Figure 1. Schematic of a simple vapor-compression still.

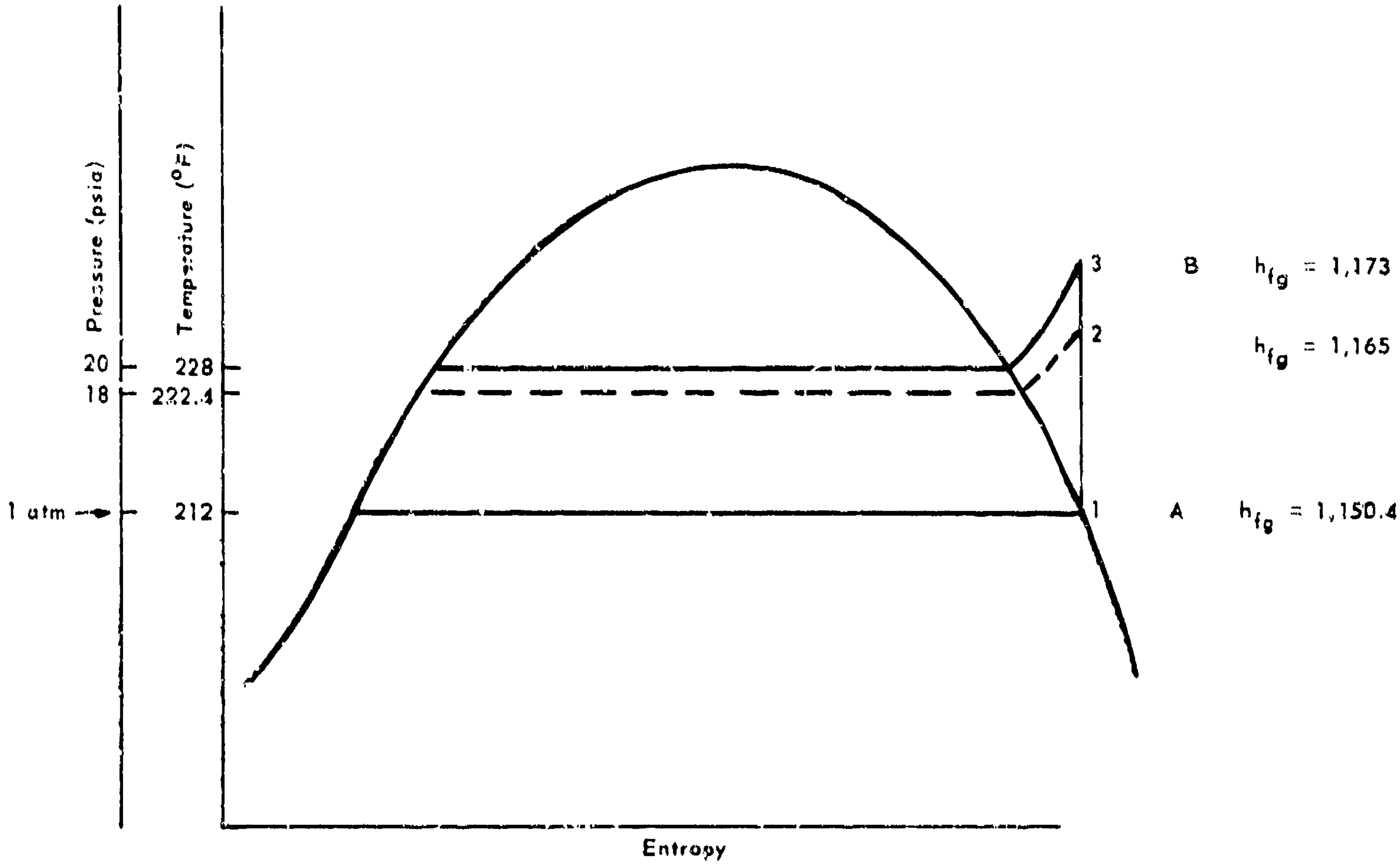

Figure 2. Schematic temperature-entropy diagram for a vapor-compression still (no scale).

The values shown would be typical for a vapor-compression machine operating with a 16°F temperature differential, boiling to condensing side, and with the low side at atmospheric pressure. On such a cycle, with isentropic compression, the water-fuel production ratio on a weight basis might be

$$\frac{\text{lb product}}{\text{lb fuel}} = \frac{\text{energy available as shaft work}}{\text{enthalpy change in compression}}$$

$$= \frac{\text{(thermal efficiency) (Btu/lb fuel)}}{h_2 - h_1}$$

$$= \frac{(0.3)\ (18{,}500)}{1{,}173 - 1{,}150.4} \approx 245 \text{ lb water/lb fuel} \qquad (1)$$

Similar production rates are routinely achieved in less than perfect machines of small size, so it is obvious that the cycle stake points illustrated are not difficult to achieve in a simple vapor-compression cycle.

If the temperature on the high side could be effectively reduced to, say, 222.4°F corresponding to a saturation pressure of 18 psia as indicated at 2, Figure 2, then the production rate on a similar cycle basis would rise to about 380 pounds of water per pound of fuel in an ideal machine. Such large potential gains are the basis for the heat-transfer research and theoretical and experimental studies discussed in this report. Clearly, the efficiency of the vapor-compression cycle is limited only by the temperature difference necessary to accomplish the heat transfer from the condensing steam to the boiling brine.

NEED FOR THIN-FILM EVAPORATION

In the usual process device in which heat is transferred to a fluid through a solid partition such as a thin metal wall, the rate of heat transfer can be related to the thickness of a finite laminar boundary layer or quiescent film.

If flow is induced by forced convection, the rate of heat transfer can be described by the well-known Dittus-Boelter dimensionless equation (McAdams, 1954):

$$\frac{hD}{K} = 0.023 \left(\frac{DG}{\mu}\right)^{0.8} \left(\frac{c_p\mu}{K}\right)^{0.4} \qquad (2)$$

for which a particular tube, fluid, and a small temperature range reduces approximately to the dimensional equation, $h = CV^{0.8}$. C is a constant involving the combined variables in the rest of the equation; V, the velocity, is found from G.

Such an equation applied to the vapor-compression still would only apply if the high-pressure steam, state 2, Figure 2, were slightly above the saturation temperature at state 1, but not high enough to induce boiling within the tube. The liquid would be heated on traveling upward through the tube and, upon pressure release at the top of the tube, a small amount of steam would be formed by flashing, depending upon the amount of superheat of the water above the saturation temperature at state 1. The still would be functional but inefficient in that very large tube areas or high velocities induced by forced pumping would be required. The first arrangement would be bulky and unduely expensive. The second, with forced convection, would be inefficient in that excessive pumping power would be required. The usual simple vapor-compression still operates on such a cycle only while being brought into production. During continuous operation, steam is usually formed over a considerable length of tubing, taking advantage of the high heat-transfer rates possible with nucleate boiling. The flash still described above would have the single potential advantage that scaling would be minimized, since boiling would not occur on the metal surface. Some scaling, or so-called "temporary hardness," could be expected from compounds precipitating at elevated solution temperatures.

If the steam pressure and temperature at state 2, Figure 2, were raised so that the surface temperature of the metal at the lower portion of the tube were significantly, say 7 to 10°F, above the local saturation temperature, the rate of heat transfer would be materially enhanced by local disturbance of the laminar film, Figure 3, from within. Equation 1 would no longer hold, but the rate of heat transfer would still be responsive to the rate of fluid flow; the situation is intermediate between forced convection and active nucleate boiling. With further increase in steam pressure and subsequent higher metal temperatures, active nucleate boiling, eventually without recondensation of the bubbles, would occur. Figure 4 reports University of California (1951) experiments of subcooled nucleate boiling at varying flow rates, and common boiling characteristics, independent of flow rate, at large temperature differences. This plot clearly shows the importance of metal temperatures relative to saturation temperatures and the need for small differences. Economical operation of vapor-compression still does not allow operation at high flow rates or large values of θ_{sat}. If it did, prodigious quantities of distilled water could be produced in a very small evaporator. Heat-transfer rates of 3 to 4 x 10^4 Btu/ft^2, hr can be accomplished with large values of θ_{sat} (Figure 5). Figure 5 is a typical log-log plot of heat-transfer rates versus the local point temperature difference between the metal wall and the saturation temperature of the boiling liquid. Very high pumping rates, which would yield good heat transfer as described by Equation 1, are not consonant with good thermal economy, as they may be obtained only with excessive pumping power.

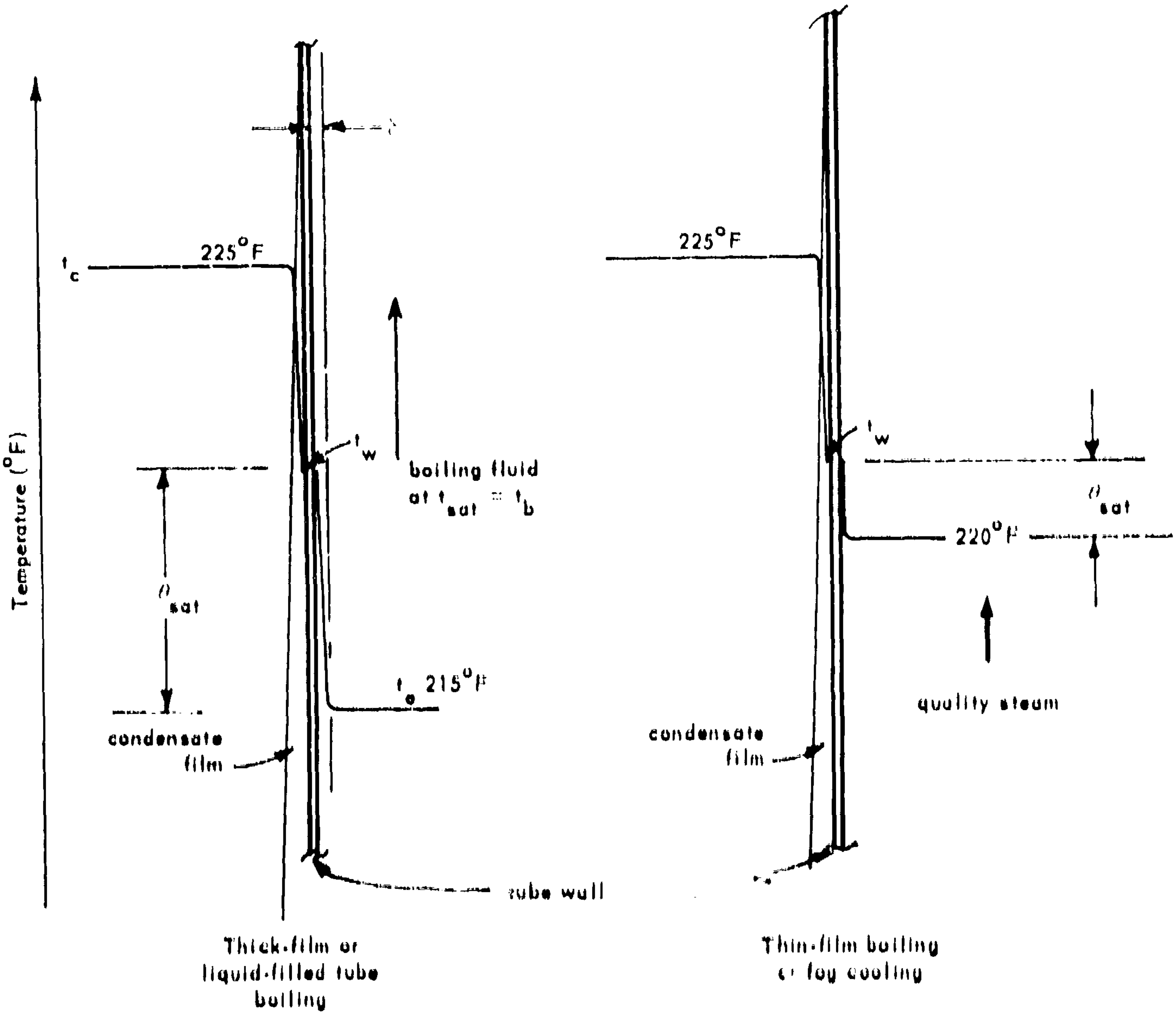

Figure 3. Schematic representation of relative film thicknesses, showing effect on total temperature drop and θ_{sat}.

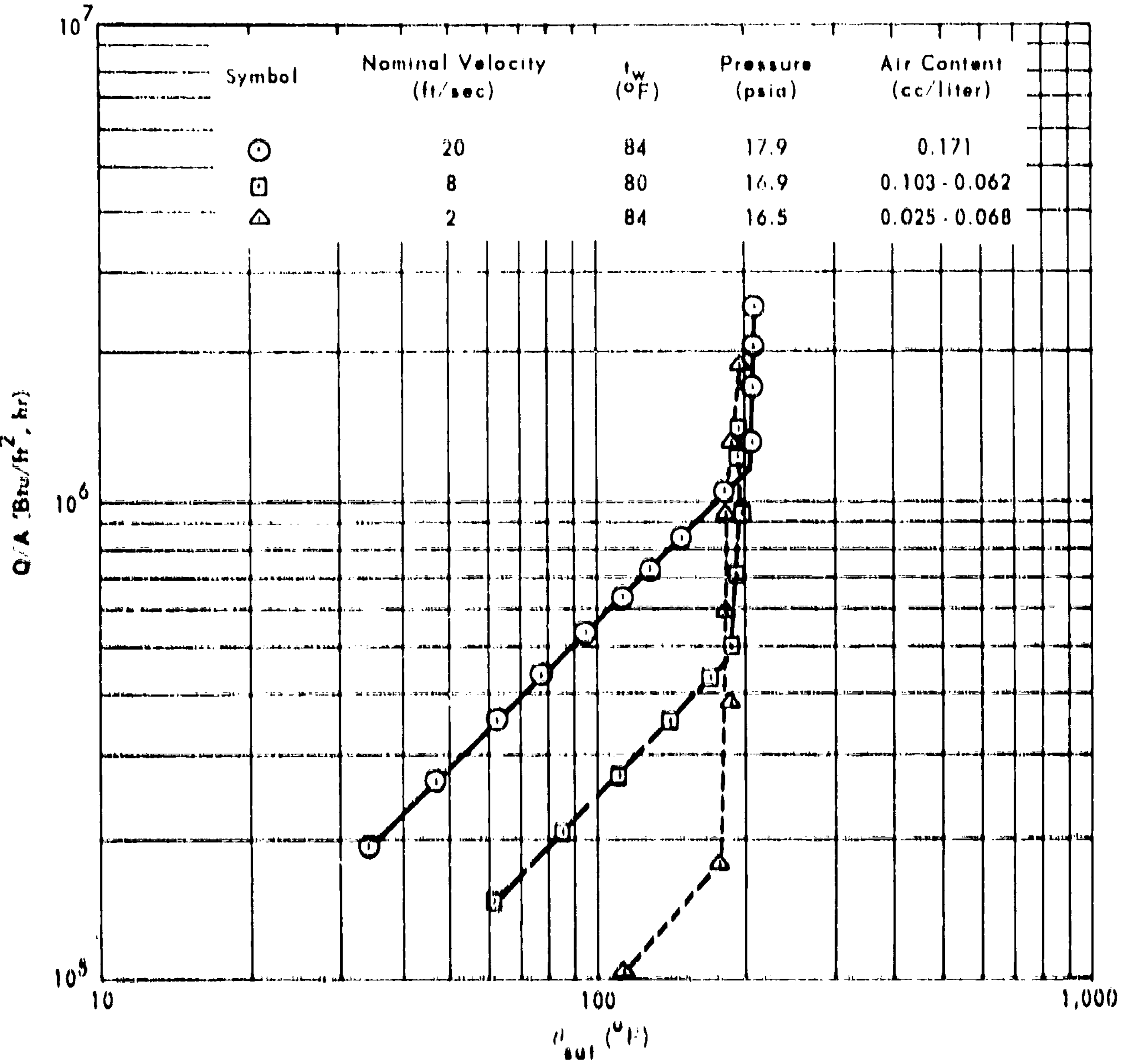

Figure 4. Heat flux density (Q/A versus θ_{sat}) for a nickel tube. (From University of California Report, AEC Contract AT-11-1-Gen-9, of March 1951.)

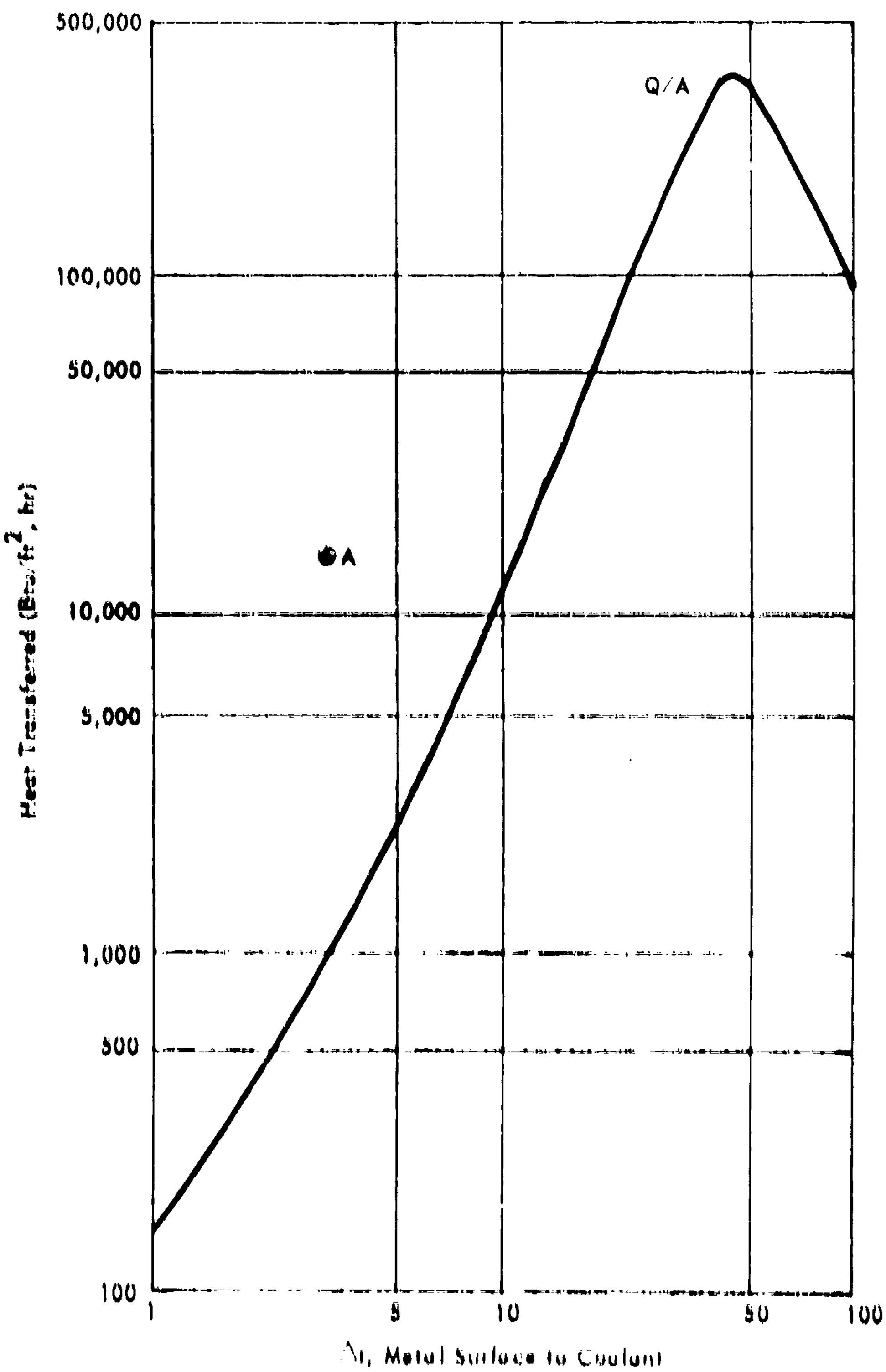

Figure 5. Graph of water boiling at 1 atmosphere outside a horizontal submerged tube. (From McAdams, 1954.)

There is, however, an area of forced convection plus nucleate boiling where pumping at reasonable rates produces an overall economy. This mode of operation has recently been used in practical vapor-compression stills. Schematically, the eventual effect of attempting to obtain very high heat-transfer rates by pumping can be seen in Figure 6, a plot of calculated total pump power added to compressor power. Values of h for various velocities were extracted from curves by McAdams (1954). The simplifying assumption is made that the efficiencies of the circulating pump and vapor compressor are the same. If one were significantly better than the other in mechanical efficiency, the curve would be the same shape, but displaced to the left or right. The more efficient the pump, the higher the flow rate for a minimum power expenditure per unit of distillate. A similar trade-off arises in connection with enhancing heat-transfer processes of mixed water-steam, currently referred to as fog-flow. Here, the laminar film across which heat must transfer is apparently reduced in thickness by using a system in which it is inherently physically thin. The evaporating film is continually replenished along the length of the tube by deposition of water droplets from wet steam. Circulation of the steam, however, would cause an unfavorable power balance at very high rates.

The above discussion reflects the long-time preoccupation of investigators of boiling heat transfer with the mechanism of destruction of the laminar film, Figure 7, by forced convection and promotion of active nucleation. Here, nucleation was promoted by circulating a slurry of solids. The data are from McAdams (1954) and Thomas and associates (1959).

CONSIDERATION OF BOILING HEAT TRANSFER

The prevalence of the use of boiling heat transfer to obtain high transfer rates in a wide variety of process equipment led to a protracted consideration of possible ways to achieve high coefficients at low values of θ_{sat}. Boiling is such an attractive approach to securing high equipment capacity with small volume and small heat-transfer surfaces that its abandonment must be with reluctance.

Literally thousands of investigations of boiling have been reported since Nukiyama (1934) first discussed variations in boiling types with increases in surface temperature. McAdams (1954) summarized the knowledge and experiments available at that writing. Up to that time little interest had been shown in the low flux, low θ_{sat} area, of such vital interest in vapor-compression distillation. The nature of bubble origination, effects of solutes, surface roughness, adsorbed air, aging, etc., on boiling at intermediate nucleate boiling rates was discussed by McAdams in reporting on many references, a few of the more interesting of which are listed in the Bibliography of this report. The data reported were empirical, and the probable lowest θ_{sat} at which boiling was observed was about 3.8°F. A minimum of about 9°F would be more typical of most devices. At lower temperature differences, heat is

transferred by convection without the benefit of agitation by bubble formation, and, as has been remarked, process equipment designed to operate at lower temperature differences requires large and expensive heat-transfer surfaces for a given production, or requires enhancement of heat transfer by forced convection.

In an important and seldom cited theoretical analysis of heat transfer in both natural convection and boiling, Chang (1957) related boundary film thickness, wave length, and wave amplitude to the difference between the temperature of the transmitting surface and the saturation temperature of the water or the temperature of the air. Transition between the various heat-transfer regimes at increasing values of θ_{sat} was explained, and the theoretical results were correlated with experimental values from the open literature. Figure 8 is reproduced from that source. This clearly shows that the vigor of the disturbance which tends to remove the boundary layer in boiling diminishes progressively at lower temperature differences, and that, unless a method can be found for encouraging the formation of steam bubbles at low temperature differences, heat transfer encouraged by boiling will not be useful in the range of a few degrees of θ_{sat}. The nature of the conclusive arguments against ebullition at very low values of θ_{sat} were shown by Y. Y. Hsu (1962) in a paper which correlated experimental evidence with an analytical expression for the conditions at which boiling would occur. Figure 9 from that paper shows that for pool boiling from a strip, boiling will not occur below a comparatively high heat flux and, in Figure 10, a high θ_{sat}.

There is, however, recent evidence (e.g., Bonilla, 1963) to indicate that surface roughening of particular kinds may allow boiling with a θ_{sat} as low as 4°F if the spacing of the ruled grooves, for instance, is optimum — about 2 diameters of the steam bubbles at the time of release. It is entirely within the realm of possibility that a combination of surface-tension modifiers, specialized surfaces, and possibly other methods might allow vigorous boiling with a very small surface superheat; and boiling would again be a prime method for achieving economical designs of vapor-compression stills.

Many aspects of boiling, such as effects of roughened surfaces, soluble and insoluble additives, and changes in pressure, were reviewed in the preliminary phase of this investigation; a few of these are listed in the Bibliography. A still larger digest of boiling literature is found in a paper by Schmidt (1962).

In review, vigorous disturbance of a quiescent boundary layer adjacent to a heating surface reduces the effective thickness, δ, of the layer and increases the rate of heat transfer. Ebullition is known to be an effective means of disturbing, like a chigger, from within, but present knowledge of the bubble-forming process limits the minimum temperature difference for boiling to perhaps 8°F or more, which is undesirably high for the vapor-compression cycle in saline water conversion.

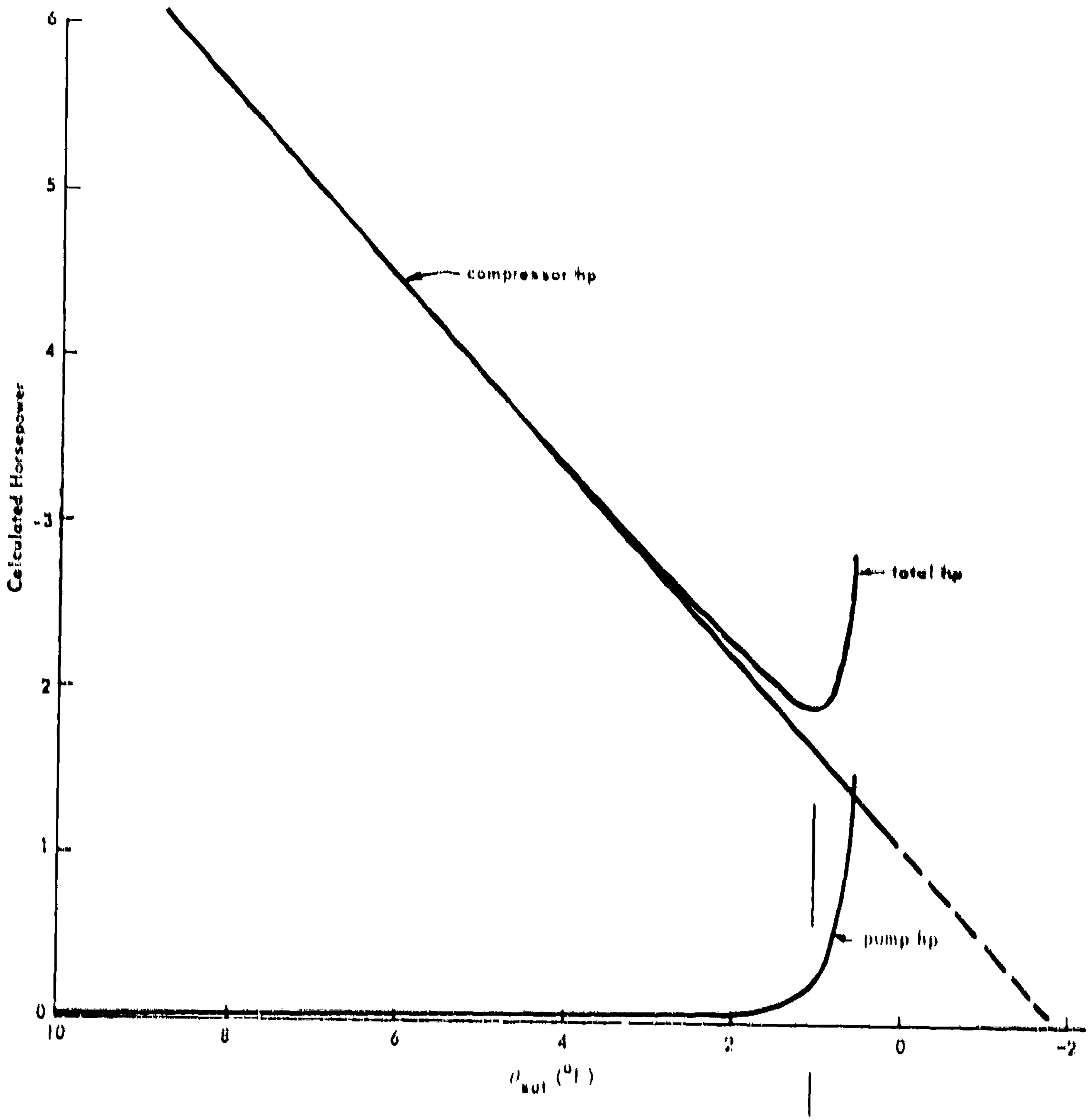

Figure 6. Calculated compressor, pump, and total horsepower per 1,000 pounds of product for 5/8 inch tube, assuming isentropic compression and 100% efficiency in compressor and pump. Illustrative only.

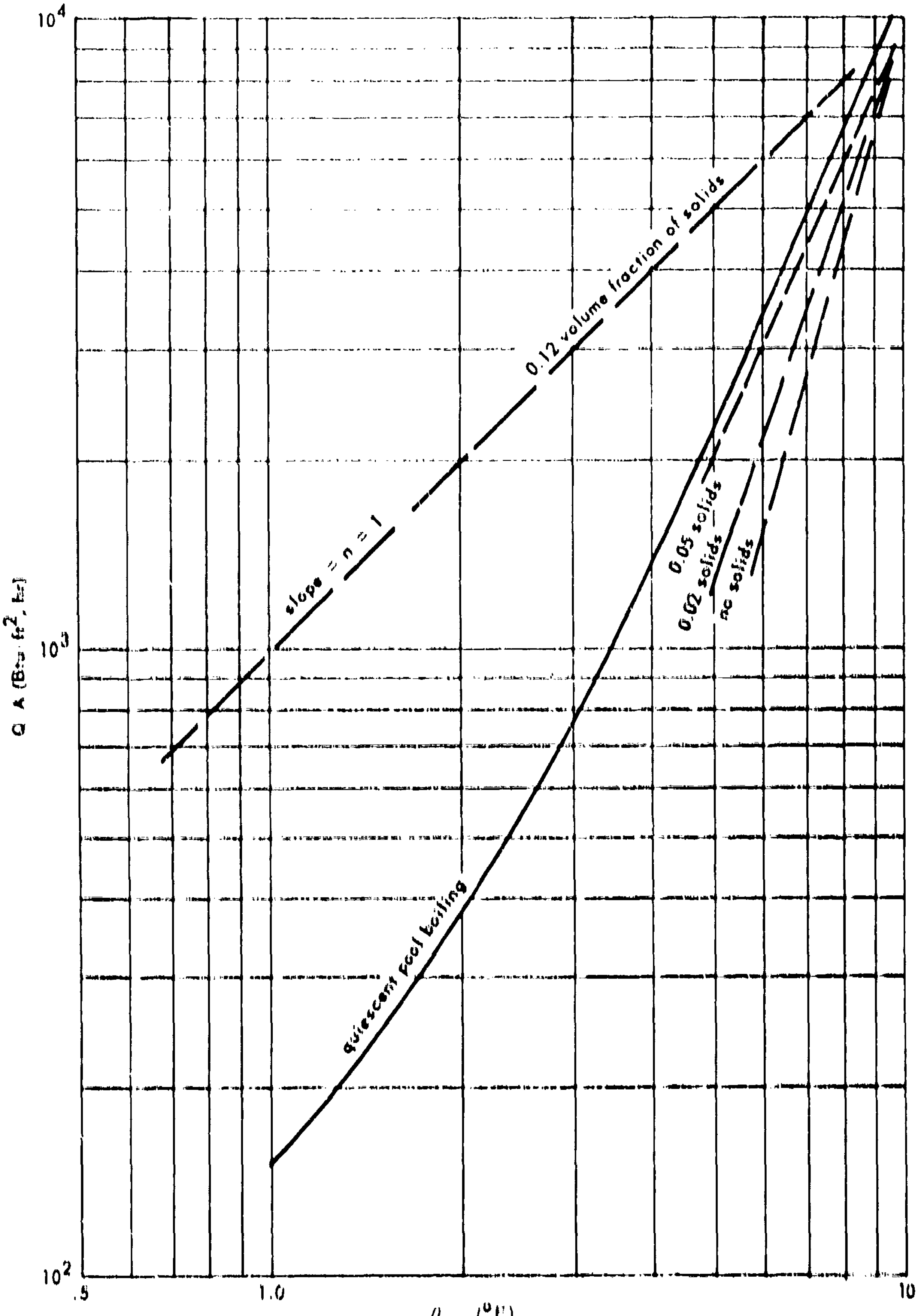

Figure 7. Effect of solids dispersed in circulating fluids on nucleation. (Quiescent values from McAdams, 1954; slope values from Thomas, et al, 1959.)

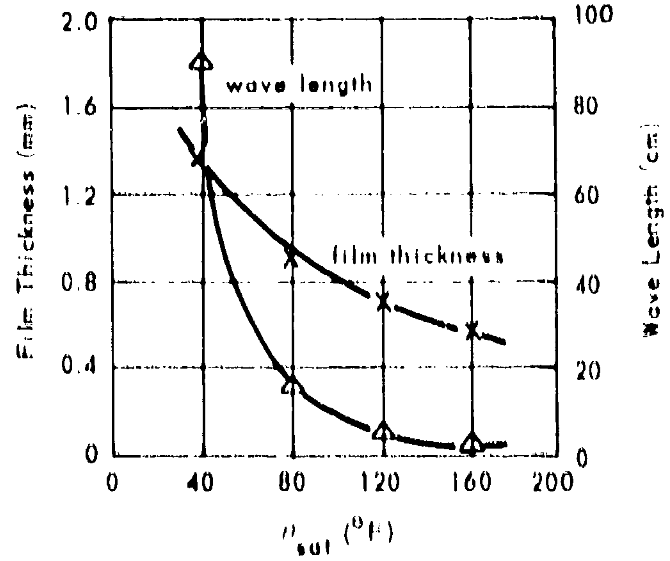

Figure 8. Relation between film thickness, wave length, and temperature difference for water at t_c = 60°F. (From Chang, 1957.)

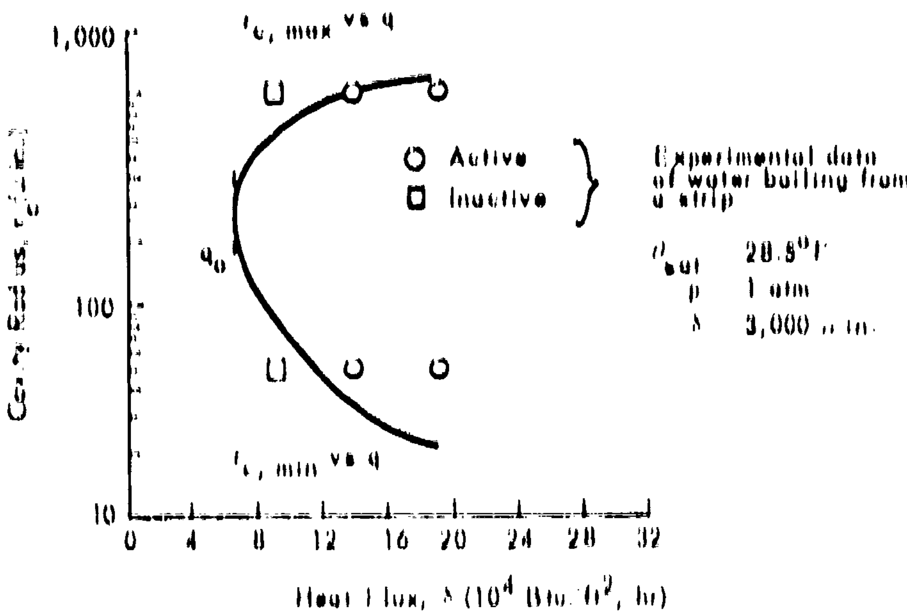

Figure 9. Activation of nucleation sites as heat flux is increased. (From Y. Y. Hsu, 1962.)

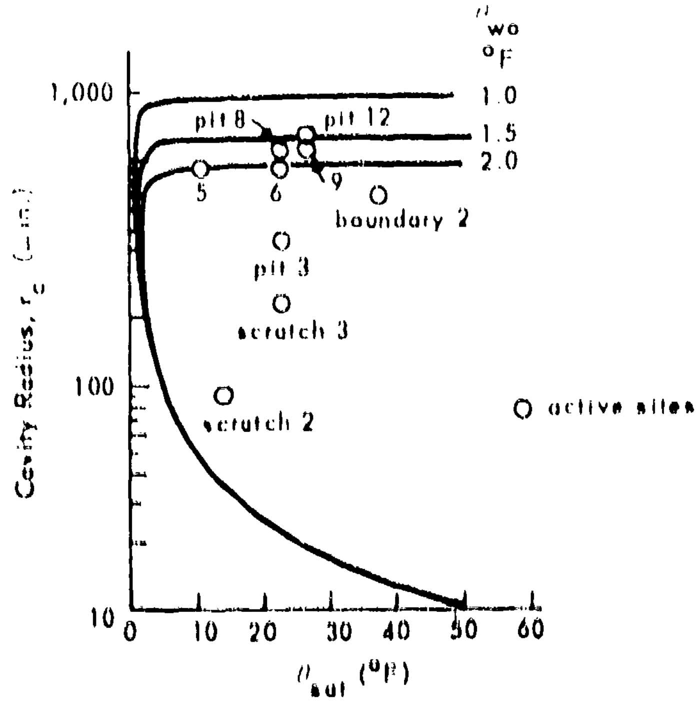

Figure 10. Size of effective cavities as function of surface-to-bulk-temperature difference, θ_{sat}, for the boiling of ether. (From Y. Y. Hsu, 1962.)

An alternate scheme to ebullition for promoting rapid evaporation from a fluid surface is to reduce the actual fluid layer to a thickness so small that its nuisance value as an insulating layer is largely removed and, hopefully, high heat transfer per unit area can be accomplished with a low θ_{sat}. The remainder of this study is dedicated to discussing or demonstrating methods whereby a satisfactory thin film might be sustained in the presence of vigorous evaporation, and to citing other research which has proposed to do this or the consequences of which can be determined to have a similar benefit.

DEVELOPMENTAL PREMISES FOR IMPROVED VAPOR-COMPRESSION STILL

Having abandoned, at least for the time being, the boiling process, as such, for securing high heat-transfer rates in an improved vapor-compression still, it is constructive to consider possible goals. Stated in outline, the following minimum requirements for the heat-transfer process sought are proposed as guides:

a. High values of the film coefficient on the boiling side should be possible, thus reducing the heat-transfer area necessary for a given production and keeping costs for equipment low.

b. The high film coefficients, (a) above, should be possible at low values of θ_{sat}, so the compressor power to raise the saturation temperature will be low.

c. The film should be stable, and the method of replacing evaporated fluid continuously should be such that the film will be of uniform thickness insofar as possible.

d. The feed mechanism, (c), should be such that dry areas will be avoided, or if they occur, that the surface will be immediately rewetted.

e. Evaporation should occur at essentially constant pressure over the entire evaporating area, inasmuch as the condensing high-pressure side is at a constant pressure, and optimization at a low overall temperature would require little or no variation in evaporating temperature.

f. The system selected should be adaptable to construction using common materials, shapes, and fabrication methods, and be mechanically simple.

g. The process should lead to no scaling, or at worst, readily removed scale us ig simple techniques.

h. The process should be usable over a span of temperature and pressure ranges so that a favorable area of operation can be selected as dictated by ambient temperature, scaling problems, venting problems, etc.

i. Total power requirements, pumping plus compressor power, should be as small as possible.

Thin-film evaporation appears, from present evidence, to have many, if not all, of the desired characteristics, provided it can be maintained in a practical machine.

The efficacy of a simple steam-water (wet steam) mixture to provide a suitable thin film full length of the tube has not been demonstrated under conditions which might lead to scale deposition from a brine; the work of Dengler and Addoms (1956) clearly indicated that, at least under controlled laboratory testing, deposition with a selected radioactive solute did not occur so long as the steam quality was less than about 70 percent. Mumm (1954) also reported increasing boiling-side film coefficients with increasing steam quality up to 50 percent, and indicated the probable cause as being boiling in a thin film.

The developmental work apparently necessary to devise reliable vapor-compression stills is that which will perfect methods of water injection into the recycled steam, thus reducing its quality and insuring even distribution. It must also provide for continuous wetting to prevent deposition of scale; this may limit the length of tubes or the maximum steam quality.

The experimental and theoretical demonstrations, as reported by other investigators, of the capability of a thin film of evaporating liquid to cool a surface do not describe in detail a practical method of distributing the necessary feed water (brine, in the case of sea-water distillation) at the tube entrance and maintaining a suitable thickness as the steam-water mixture traverses the tube and part of the water evaporates. Some schemes which might be tried are listed below, together with the reasons why their particular features are of interest.

In the simplest case, recirculated steam at a superpressure suitable to provide the necessary pressure drop in the tubes would be bled off the prime steam compressor at an appropriate state, Figure 11. With sufficiently fine dispersion in the nozzle, a uniform mixture of wet steam and brine droplets would divide among the various tubes, and some of the droplets would immediately plate out on the tube walls as a thin film, where they would evaporate and increase the quality of the wet steam stream. A sketch of this is shown in Figure 12. The quality of the entering steam might be something like 5 to 15 percent, and the flow quantities such that the exit steam quality would be well below 70 percent, a critical value for at least certain flow rates. Stein and associates (1962) describe such a system investigated to determine the efficacy of a wet steam fluid in reactor cooling; they called this "fog flow." They describe some simple nozzles and experimental results of their use, which may be of assistance in developing a system suitable for entraining the necessary brine. In the actual case, the thin film would undoubtedly not be of constant thickness along the length of the tube, but would reduce as the steam quality increased and the velocity increased as a result of the volume increase. Also, fewer drops would be available for maintaining a given film, and the increased turbulence at higher velocities would tend to deplete the film by erosion. Some indication of the relative velocities and their effects on film thickness is shown pictorially in Figure 13.

Presumably the very high rates obtained at moderate values of θ_{sat} by Sani (1960) may not have been with fully developed nucleate boiling, but from a surface evaporation of a very thin water film. In one case (point 5, Run 12) a value of h_b of 4,510 Btu/ft^2, hr, $^{\circ}$F was reported at a θ_{sat} of only 3.1°F. This point is plotted as point A, Figure 5, at a Q/A of 3.1 x 4,510 = 14,000. The steam quality at this point was 6.6 percent, rather nominal. However, this still might be an uneconomical point of operation for a vapor-compression still, depending upon the pressure drop and resulting power loss in pumping the steam-water mixture. Other runs by Sani at similar conditions did not produce such favorable results, although all were good when compared with usual boiling results.

Lustenader and associates (1959) describe a mechanical system for maintaining a thin film of evaporating fluid on the interior of a large-diameter (several inches) tube by spraying and immediately wiping with moving, pressure-seated brushes

or wiping blades. Several wiper materials were tried, with carbon selected as the best of those used. The overall heat-transfer coefficients achieved — as high as 8,000 Btu/ft^2, hr, $^\circ$F — included the effects of very effective film condensation on the outside of the tube on small-radius longitudinal grooves milled into the surface. Surface tension removed the condensate from the convex to the concave, or valley, portions, where it drained away by gravity. The high overall coefficients were achieved at just over 1°F total temperature difference; and referring to Figure 2 and Equation 1, it is obvious that low temperature differences of this order will allow very high water-fuel rates, when considering the energy required from compression. These tests indicated little or no scaling, essentially in agreement with the work of Dengler and Addoms (1956).

A considerable portion of Stein's (1962) work is devoted to the formulation of a mathematical model of the plating out of water droplets from wet steam. This model will, if practicable, be used in analyzing future experimental work on this effort. It was not applicable to the data taken in the experimental work reported for CAN-2 program to date, so was not tested in that program. It is doubtful if even such a detailed model as that formulated can describe the entire phenomena by first-principle methods. Certain simplifications and assumptions may not be justified. First, the size of the droplets must be a continuum over a finite, but a considerable range; two sizes were assumed for simplification. Second, there was in the development a repeated reference to the diffusion of droplets by Fick's law, which seems unlikely since some elastic properties must pertain to have this so. Coalescence probably usually occurs upon impact. Occasional successive splitting of the coalesced droplet may immediately occur, but no experiment demonstrating this has been cited.

In the absence of a tractable mathematical model of the type Stein (1962) attempted, it is proposed that the heat transfer be described as a function of velocity and quality alone by a dimensionless equation. An intermediate consideration would be the effective thickness of the deposited, evaporating film, Figure 12. The following system of nonspecific equations should establish an adequate framework for the development of suitable design equations for full-scale equipment, even though they describe the effects better than the causes. They are, therefore, only a start.

First, the well-known Fourier's law of conduction for steady flow of heat in one dimension,

$$Q = \frac{-KA\Delta t}{\Delta X} \tag{3}$$

describes the rate of heat flow across a thin film of water in nonturbulent flow, if it is assumed that the surface of the film in contact with the steam is essentially at the saturation pressure of the steam. A further requirement, and one proved in the two simple experiments reported later in this study, is that the metal-to-fluid temperature difference be below that necessary to produce ebullition; molecules of water escape as steam at the steam-water interface as a consequence of their having sufficient energy and being headed in the correct direction. The film simply evaporates, and internal agitation does not sensibly expedite the heat transfer across the fluid film.

Defining $Q/A\Delta t = h_e$ and assuming

$$\delta = \text{constant in } y \left[\text{not } f(y)\right]$$

$$\delta = f(V^n, x_o)$$

$$h_e = f(K, \delta)$$

therefore

$$h_e = f(K, V^n, x_o) = C_1 f(V^n, x_o) \qquad (4)$$

and possibly

$$h_e = f\left(V, x_o, \frac{Q}{A}\right) \qquad (5)$$

all over a limited temperature and pressure range, for which physical properties would be approximately constant.

As a preliminary attempt at the design of a one-tube experiment for developing suitable design constants and exponents in equations such as those above, approximate extreme values were assumed for both the condensing and evaporating surfaces of h_c and h_e of 30,000 Btu/ft^2, hr, $^\circ$F. With the tube assumed, Figure 14, the overall coefficient would be about 12,700 Btu/ft^2, hr, $^\circ$F, and the overall temperature difference between the saturated condensing steam and the evaporating steam stream would be 2.36°F. If such a cycle, shown in Figure 14, is indeed possible in a practical machine, then the product/fuel ratio on a weight basis would be

$$\frac{\text{wt product}}{\text{wt fuel}} = \frac{\text{(engine efficiency) (heat values of fuel)}}{\text{increase in enthalpy in compression}}$$

$$= \frac{(0.30)\ (18,000)}{(1,153.7\ -\ 1,150.4)} = 1,640 \qquad (1)$$

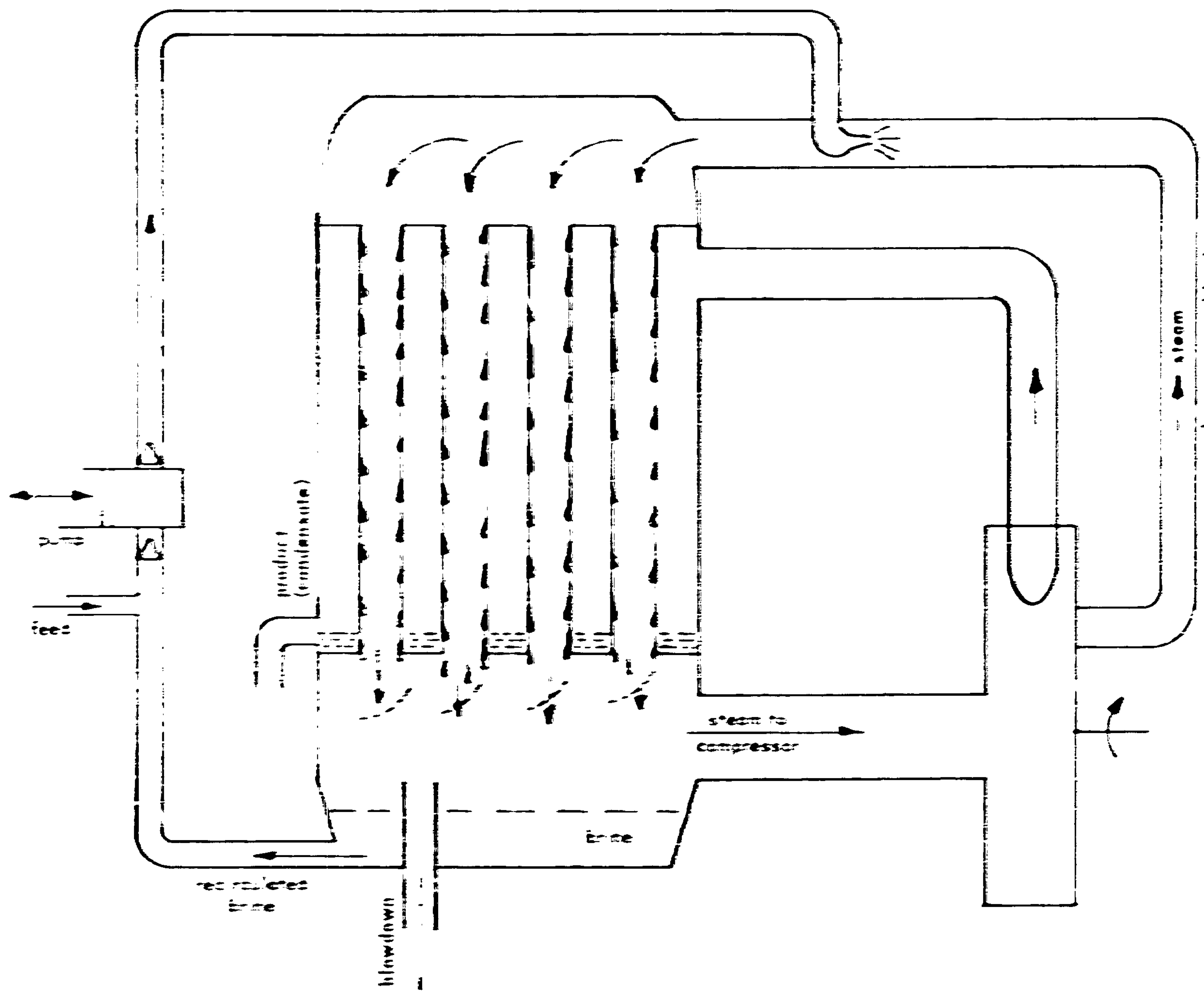

Figure 11. Schematic of thin-film vapor-compression distillation unit with film maintained by spray in recirculated steam.

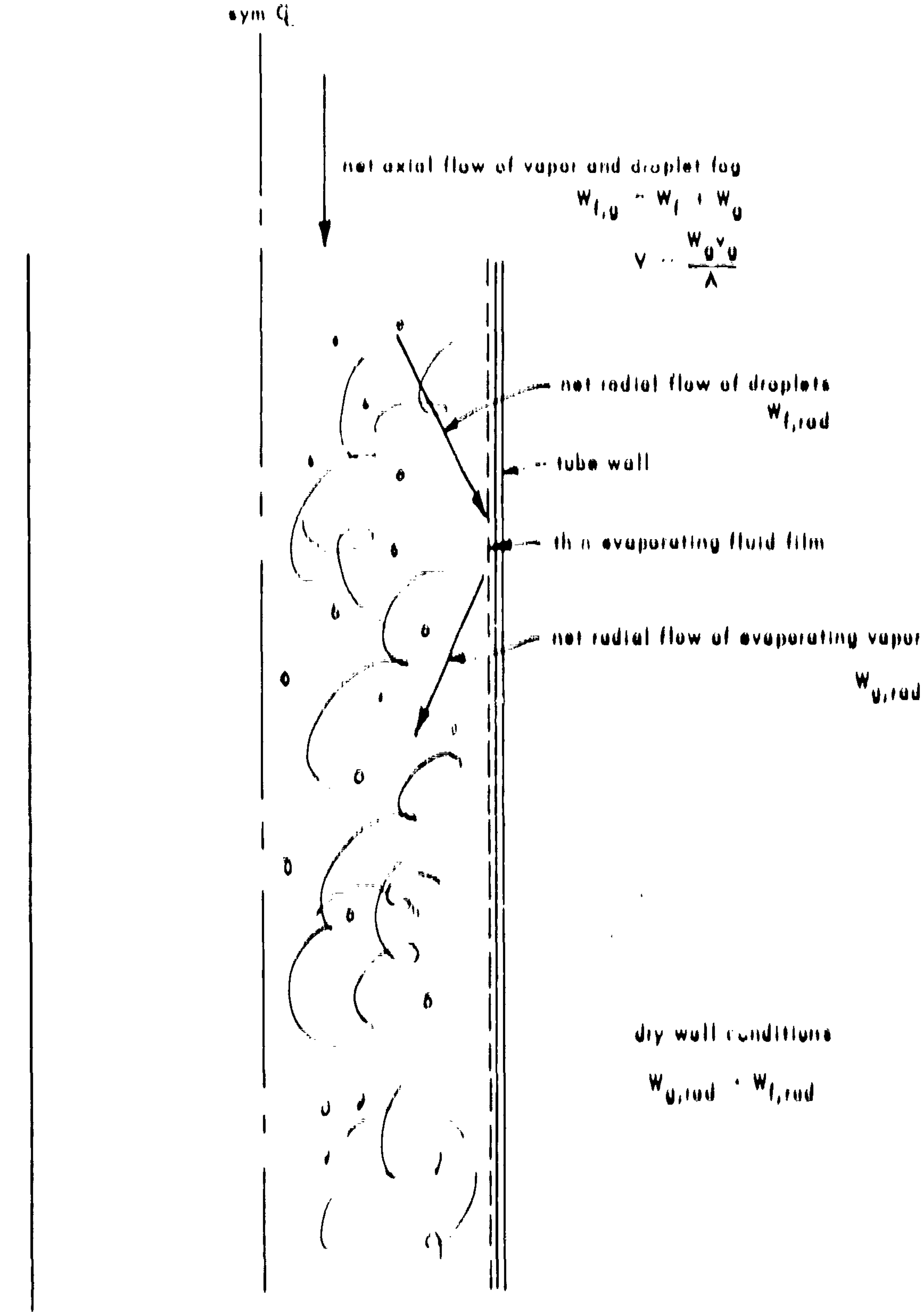

Figure 12. Schematic representation of formation and evaporation of a thin film of fluid from particles carried in a vapor.

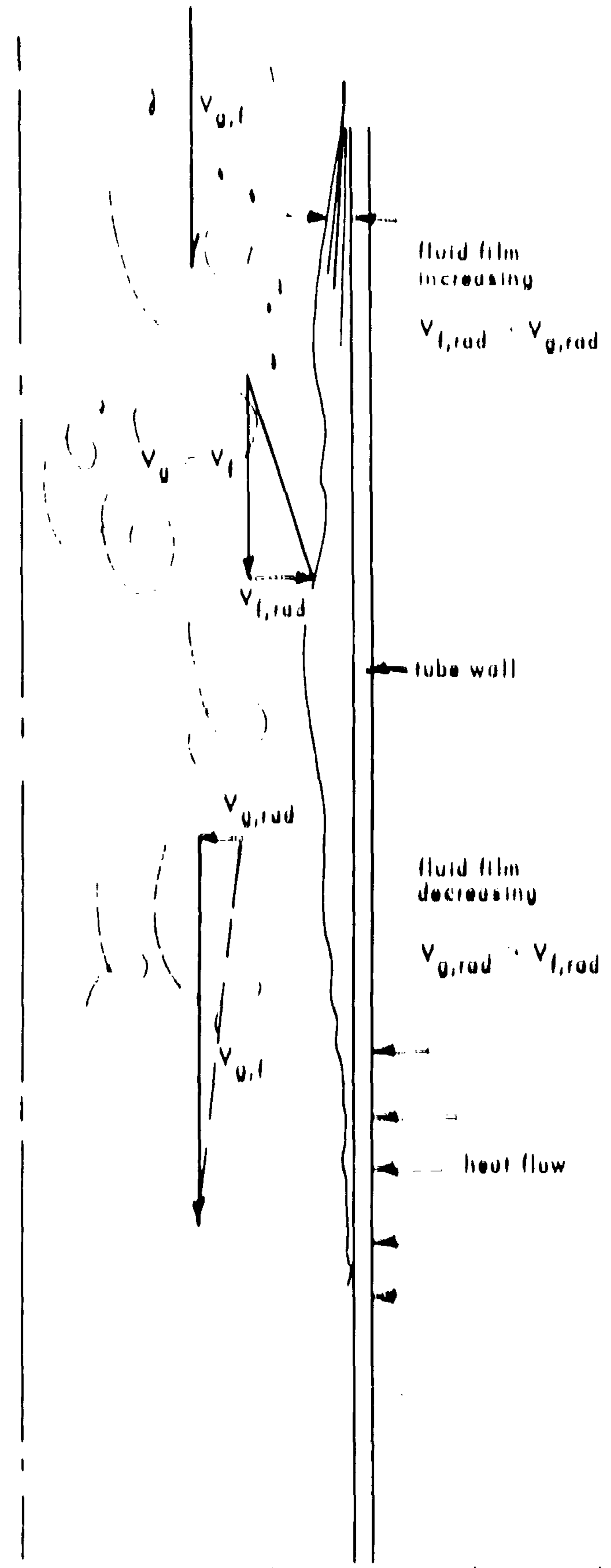

Figure 13. Schematic representation of important velocity relationships in determining thin-film thickness.

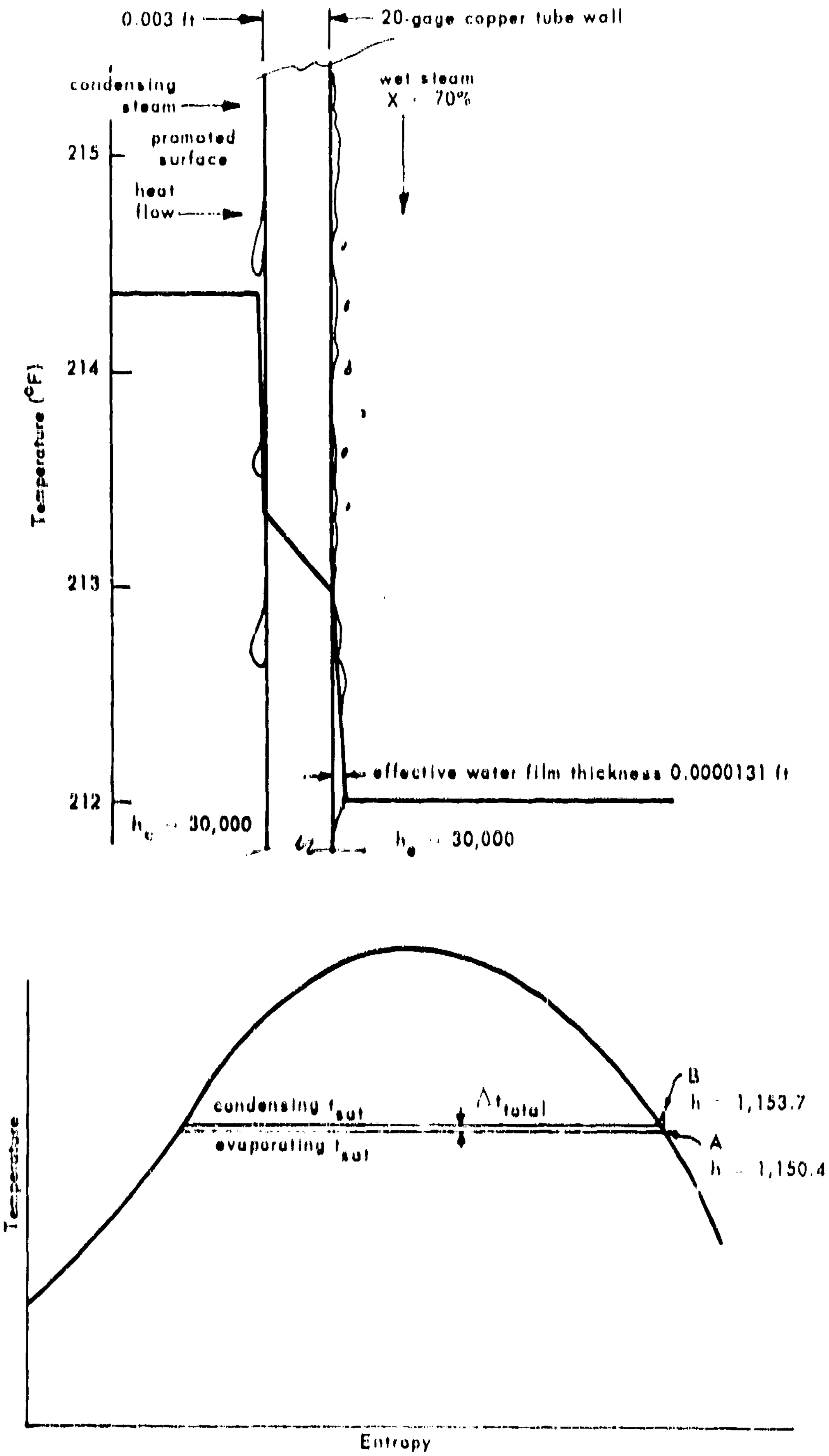

Figure 14. Possible temperature-entropy diagram and schematic of temperature drop for vapor-compression still with small temperature drop.

The calculated thickness of the evaporating water film is about 1.31 x 10^{-5} feet, or 0.000157 inch. From a review of the pertinent references cited earlier, maintenance of such a thin evaporating film appears to be entirely feasible and, for a tube perhaps 2 or 3 feet long, loss of evaporating film unlikely. Dengler and Addoms (1956) used a radioactive tracer technique to detect dry wall conditions and found that for a given steam quality and flow rate the conditions could be predicted with a high degree of certainty. At the higher steam qualities of vapor, dry wall conditions occurred at lower flow rates than those for low steam qualities. They attributed this to an unspecified change in flow conditions, but if the film model shown in Figure 12 is correct, it can probably be explained more simply in terms of the maintenance of an adequate water film. At high steam fractions and high steam flow rates, the evaporating film would tend to be wiped away by turbulence at the steam-water interface. If so, this will be a fortuitous circumstance in the development of practical stills using fog flow, as high flow rates would require excessive turbine power for steam circulation. They would also result in a relatively high pressure drop, which would in turn be undesirable in maintaining a constant and low temperature difference, steam to steam.

Because the enhancement of heat transfer to a fluid always involves decreasing the thickness of the boundary layer through which heat is transferred essentially by conduction, it is instructive to calculate the effective thickness of the boundary layer for any case, using the simplifying assumption that the entire temperature drop occurs through the boundary layer, and in proportion to its thickness. This can obviously not be precisely so since the physical properties of the fluids change with temperature. A closer than necessary approximation can be obtained by assuming properties at the mean temperature, wall to bulk fluid. For a typical value of Q/A, h = 315 for forced convection at low velocities of water being heated, near the boiling point of 212°F and with a Reynolds number of 10,000 in a 1-inch-ID tube. A hypothetical boundary layer of 0.003 inch would at that temperature give the same resistance assuming $\Delta t = 10°F$ and $x = KA\Delta t/Q$. In the above sample calculation, h was calculated according to the familiar Dittus and Boelter (1930) equation:

$$\frac{hD}{K} = 0.023\,(N_{Re})^{0.8}\,(N_{Pr})^{0.4} \qquad (2)$$

Using experimental data from McAdams (1954) for boiling at 212°F, Figure 14-1 of that reference gives a Q/A of about 9 x 10^3 for $\theta_{sat} = 10°F$; an equivalent thickness by Equation 3 would be some 0.00045 inch. For the case cited by Putnam et al (1961), with U = 4,500 Btu/ft^2, hr, °F, an equivalent evaporating liquid film thickness calculated by the same technique would have to be less than 0.00009 inch. The latter were able to maintain such a film by rapidly spinning the heat-transfer surface while

spraying on the liquid. With a fully wetted surface, the fluid would stay only a short time and the maintained film would be approximately a function of the centrifugal force.

DEPOSITION OF SOLIDS

The prime question to be answered in the perfection of a still based on thin-film evaporation relates to whether or not a scale will be deposited and if deposited, whether it can be continuously or intermittently removed. Two cases for scale deposition are apparent. First, and most obvious, is that related to temporary hardness. Sea water contains, among other compounds, some that are less soluble at elevated temperatures than at low. Heating produces a supersaturated tendency which frequently leads to spontaneous deposition on heat-transfer surfaces, introducing an insulating scale barrier ruinous to economical operation of the equipment. In vapor-compression stills, because of the need for low overall temperature differences in accomplishing good water/fuel rates, such scale cannot be tolerated. Presumably, the problem with this form of scale, usually called "temporary hardness," would not be different for a thin-film device than for a tube nominally full of water at the entry. Large evaporation rates in terms of fractions of brines introduced would, however, lead to conditions in which supersaturation would be more likely. The usual solution would be to reduce the temperature of evaporation to that of maximum, or near maximum, solubility. For calcium sulphate, about 130°F or lower would be desirable.

The second form of scale would normally occur only with evaporation of the metal surface to a dry condition. However, with a very thin film it is entirely possible that occasional temporary dryness, or something so close to it as to be practically indistinguishable, would occur. In fact, it is conceivable that very high evaporation rates and extremely high evaporation-side coefficients will prove to be uniquely related to evaporation of intermittent droplets which only partially cover the surface. In the simple "hot plate" experiment described later on in this report, the high transient rates observed from the disappearing film appeared to usually be associated with intermittent patches of dry surface.

BUBBLY EVAPORATION

An unobvious situation was observed in the small copper hot plate experiments described later. The observed metal surface temperatures were lower than would be required for ebullition, and the resulting apparent heat transfer coefficients were quite high. Whether or not such bubbly evaporation can be obtained in a useful distillation apparatus is uncertain, but it presents some interesting possibilities as a

method of production of wet steam for feed to the tubes of a thin-film evaporator, using low-velocity feed water at the source. Some excess temperature would be needed to induce local boiling at the very entry, as bubbly evaporation appears to be an unstable condition which can be initiated only by boiling. Some excess temperature above that of the condensing steam is available in the incoming superheated steam. Bubbling could also perhaps be initiated electrically.

In most of these discussions, it is assumed that the water-steam mixture would be advantageously introduced at the top of vertical tubes and the flow would be downward. For the case of bubbly flow feed mentioned here, introduction of preheated feed at the bottom of closed-end tubes would be an obvious approach. The small experiment shown schematically in Figure 18 later on in this report illustrates this concept; a full-length tube might be continuously fed by a small tube or orifice. Such an arrangement, if workable, would negate the use of a steam bypass, as shown in Figure 12.

The initial decrease in wall temperature would result from a decrease in liquid head, resulting in a decrease in saturation temperature in the liquid at the upper surface of the boundary layer (Chang, 1957, and Bergles and Rohsenow, 1964). The former of these references describes a boundary layer of thickness δ; the latter describes a method of determining the point of commencement of nucleate boiling on a typical plot of the logs of Q/A and θ_{sat}.

SMALL EXPERIMENTS

Hot Plate Experiment

To allow close inspection of an evaporating film and the phenomena believed to be responsible for the high coefficients observed by Stein (1962), Sani (1960), and by Dengler and Addoms (1956), a miniature copper hot plate was constructed which would allow evaporation from a thin film without the effects of significant transverse velocities. In its major features, it is similar to experimental equipment used by Hsu and Schmidt (1961). Shown schematically in Figure 15, the simple apparatus consisted of a right-circular cylinder of pure copper fitted with two internal electrical heating elements in its lower section. These could be wired in series or parallel and were fed by variable voltage from an autotransformer; any heat input up to about 420 watts could be obtained. Heat transfer could be calculated using the temperature drop from a couple placed above the heaters in a milled slot and from one in the exposed face. In addition, the surface temperature could be measured at any point on the surface by means of a constantan probe affixed to a simple beam. For both the traversing couple and the one buried in the surface, the copper block formed one of the couple elements, the sharpened constantan wire the other. Estimates based on observed power input, calculated and measured heat loss, and calculations

based on temperature drop through the copper block agreed consistently within about 6-1/2 percent. It is estimated that the usual error was on the order of 4 percent, with a probable maximum of about 7-1/2 percent. The limiting readings were the temperature drops, and no attempt to refine them to produce greater accuracy was made, as the experiment was intended to demonstrate, in an open-face apparatus, the changing heat-transfer modes in a disappearing thick film of water.

Since the cat-whisker thermocouple technique is not generally used, it is probably worth noting that the surface temperature measured by the bedded couple, A, Figure 15, consistently agreed within 0.2°F.

The boiling surface was on occasion polished with fine (200 grit) carborundum paper, after which it was aged by boiling for at least 30 minutes, so that results could be reproducible. For a given heat input, the boiling surface temperature was invariably lower with the surface newly polished than it was after aging. All surface temperatures reported for disappearing films are with aged surfaces.

A run consisted of boiling away a layer of distilled water about 1/4 inch thick, during the first few minutes of which the surface temperatures were characteristic of nucleate pool boiling. When the film was reduced to about 1/16 inch and was still far too thick to produce thin-film evaporation, local boiling at selected sites stopped. The surface was either intermittently or continuously covered with large, active bubbles, and the surface temperature dropped. Because the surface temperature during this bubbly evaporation was below that normally required for nucleate boiling at atmospheric pressure (as little as 1.5°F above the saturation temperature of distilled water), it can only be concluded that a true thin film was left by the lifting of a considerable portion of the water cover as large bubble materials, and that evaporation occurred without nucleate boiling. Such a condition would, of course, require nucleation to form the first large bubbles. In later stages the bubbly evaporation was not continuous over the surface of the hot plate, rather, an apparently thick film of water, perhaps 1/32 inch over a given area, would lie quietly, then suddenly froth up for a while, cool the surface, and the bubbles would then die down. Sometimes bubbly evaporation would start near the edge of a patch of liquid on a dry area uncooled recently by the liquid, and hence with the superheat above the saturation temperature necessary to induce ebullition. Once a spot started to boil, the entire adjacent area would rapidly be covered for a time — perhaps 3 to 6 seconds — by the large, clear bubbles characteristic of bubbly evaporation. Depending upon the rate of heat transferred through the copper block, the bubbles might die down. This occurred when the remaining film of water became so thin by evaporation that the heat could be transferred from a more or less uniform film. For lower rates of heat input, periodic bubbly evaporation would apparently overcool the surface temperature to the point that temporarily no boiling in any form would occur, bubbling or nucleate.

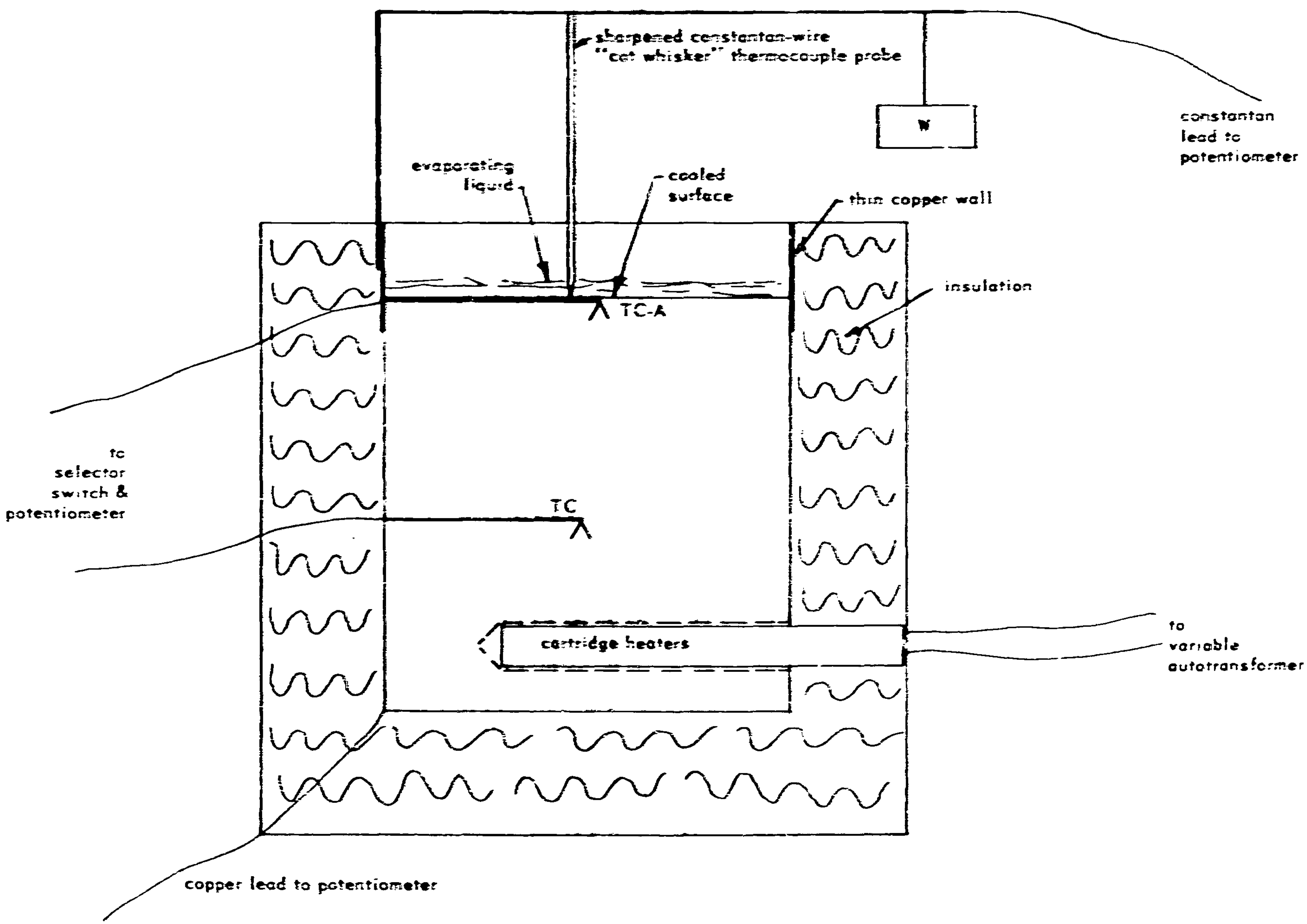

Figure 15. Schematic of small copper hot plate experiment for demonstrating bubbly evaporation and thin-film evaporation on a horizontal surface.

When the water cover on the small evaporation surface was being reduced by bubbly evaporation, the surface temperature would consistently decrease to the point where the bubbly evaporation ceased. Only a trace film of liquid remained, and thin-film evaporation commenced. When this gradual decrease in surface temperature was observed with a hand-balanced null potentiometer, the minor fluctuations, Figure 15, area A, were scarcely discernible; usually a continuous balance of the null instrument could be maintained. During the sharp decline upon disappearance by evaporation of the trace water film, the rate of temperature change was too rapid to follow with a manually adjusted null balance, so the transient surface temperature measurements of Figure 16 were made with an oscilloscope. The main features of the trace are shown in the schematic drawing, Figure 17, with various types of evaporation and heating identified. The very steep decline in surface temperature typically occurred during a period of 1 second or less, during which the surface could be observed to dry up. After a short dwell, during which heat diffused to the surface following rapid cooling by the evaporating film, the surface temperature would rise until power was shut off or the surface coolant was renewed.

Small Tube Experiment

The unexpected small metal-to-saturation-temperature differences in the bubbly evaporation with the copper hot plate regime suggested the possibility that the relatively thin film desired might be achieved in a tube, with bubbly evaporation. A second simple bench experiment was prepared, this time using a short vertical copper tube sealed at the lower end with a cork, Figure 18. Distilled water was introduced to a depth of about 1-1/2 inches before the unit was heated. The temperature at the bottom of the coolant was measured with a thermocouple projecting through the cork. The temperature at the outside of the tube was measured at regular intervals by a couple made by soldering a 30-gage constantan wire to the tube. Electrical heating tape covered with fiberglass cloth was wound tightly about the tube in a close spiral, and the unit was insulated. The inside surface temperature of the copper tube could be measured with a traveling cat-whisker probe similar to that described for the copper hot plate experiment.

Results were similar to those for the small copper hot plate, in that the metal temperature would initially rise to the point at which nucleate boiling could be expected. After a portion of the coolant charge had boiled off (there was no provision for replenishment during a run), large bursting bubbles would appear at the top of the tube, and the metal temperature would fall below that at which boiling had been initiated.

Once bubbly evaporation had been established, it remained until practically all the water from the tube had been evaporated or ejected as droplets from the large bursting bubbles. For the short tube and particular configuration used, the heat input had to be restricted to avoid forcible ejection of the main body of the

coolant. Nevertheless, active evaporation at significant heat-transfer rates could be achieved with smaller values of θ_{sat} than are usually possible with nucleate boiling.

A time versus temperature graph of a typical run for thermocouple number 8 of the schematic diagram, Figure 18, is shown in Figure 19. This clearly shows that at a constant heat input of approximately 4,100 Btu/ft^2, hr, ebullition was necessary when the water was in contact with the wall in quantity. Later, similar heat transfer was accomplished with a very much reduced temperature difference, in the portion indicated as "bubbly evaporation."

Discussion of Experiments

The potential impact of these simple experiments is clear, when considered in light of their possible effect on the efficiency of the vapor-compression still.

Irrespective of the cycle efficiency, a quantity of heat equivalent to the latent heat of evaporation must be transferred for each pound of distillate. In terms of the driving potential, which determines the relative efficiency (weight of product to pound of fuel) of the still, the high heat-transfer rates and low temperature differences would, if they can be reproduced in a practical still, increase the product-fuel rate by several times.

While no similar experiments were found to have been discussed in the literature, a reinspection of the work of certain investigators showed effects which could be explained in terms of the relationships experimentally studied here. For instance, Kutateladze (1952) discussed work by Jakob and Linke (1935) regarding the depth of cover of water over a boiling surface. Figure 20 is reproduced from that source, and clearly shows that at a depth of cover less than approximately 1/4 inch, the boiling-side film coefficient increases abruptly with decreasing depth. Presumably, it would increase asymptotically to infinity at zero depth, although there is no indication that the experiment was continued to a truly thin film. This portion of the curve of Figure 20 would correspond to the gradually decreasing surface temperature indicated schematically in Figure 17 at A. Measurements below water cover of about 1 mm would have required transient measurements, which may not have been available to Jakob and Linke in 1935.

Some of the data of Sani (1960) are replotted in Figures 21 and 22, to show an increase in evaporating side heat-transfer coefficient with increasing quality and decreasing difference in saturation temperature to tube wall temperature. While Sani presumed that there was active boiling involved here, there is evidence from the high values of h and the small temperature differences that the phase change may have been from evaporation of a thin film. Figure 23 shows data from Dengler and Addoms (1956) similar to that in Figure 21. Bromley (1963) reported experimental results with downflow boiling which would indicate, in light of the experiments

reported here, that flow was annular over most of the length of a tube, and that the evaporation (or boiling) coefficient was constantly increasing along the length of the tube as steam was produced.

Rounthwaite and Clouston (1961) reported experiments using very high-quality steam, and included the area of investigation in which the steam dried up, and was from there superheated. The evaporating film coefficients were fairly constant with increasing steam quality up to about 88 percent at 200 psig, and higher at higher pressures. Extrapolating to lower pressures, the 70-percent maximum quality for wet-wall conditions reported by Dengler and Addoms (1956) appears to be reasonable.

CONCLUSIONS

1. Evaporation from a thin film provides the best potential approach to increasing the efficiency of vapor-compression stills, based on presently known approaches.

2. Of the various approaches to sustaining thin-film evaporation, deposition of water droplets from wet steam inside a small-diameter tube is apparently the most simple of the known approaches to producing a thin film on extended surfaces.

3. Of the apparently uncertain aspects of evaporation from a thin film produced by fog cooling from a wet steam stream, droplet dispersion and potential scaling problems represent the critical areas for future investigation.

FUTURE PLANS

The experimental work which will constitute the next and, hopefully, the final phase of this study is outlined in the Appendix.

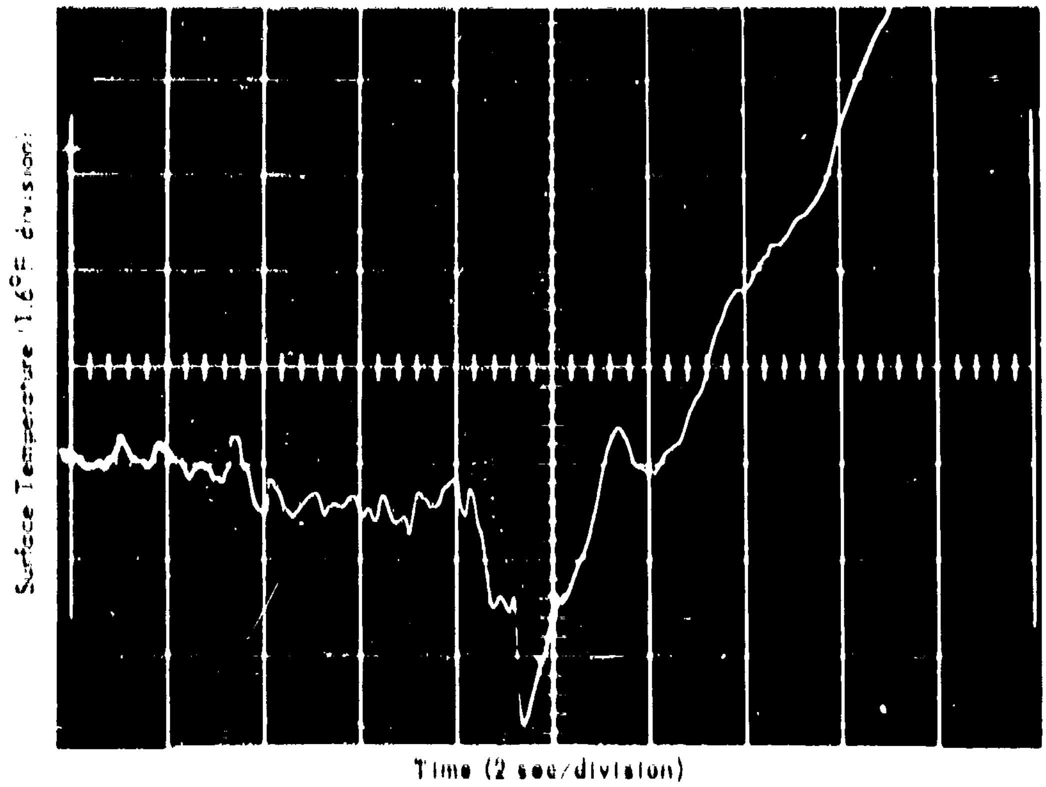

Figure 16. Time-temperature traces of surface temperature for hot plate experiment.

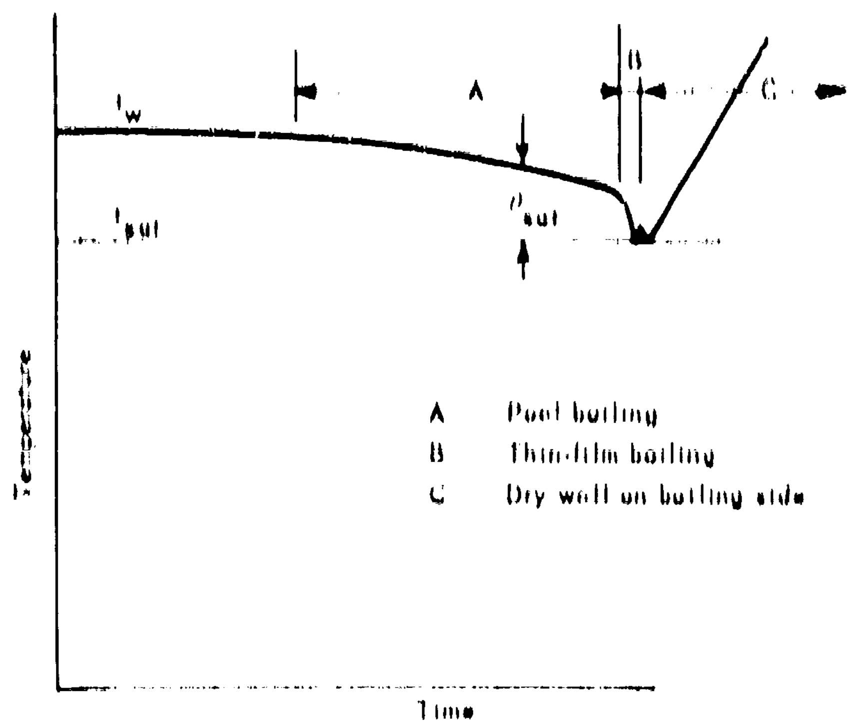

Figure 17. Schematic of time-temperature trace shown in Figure 16 with minor fluctuations ignored.

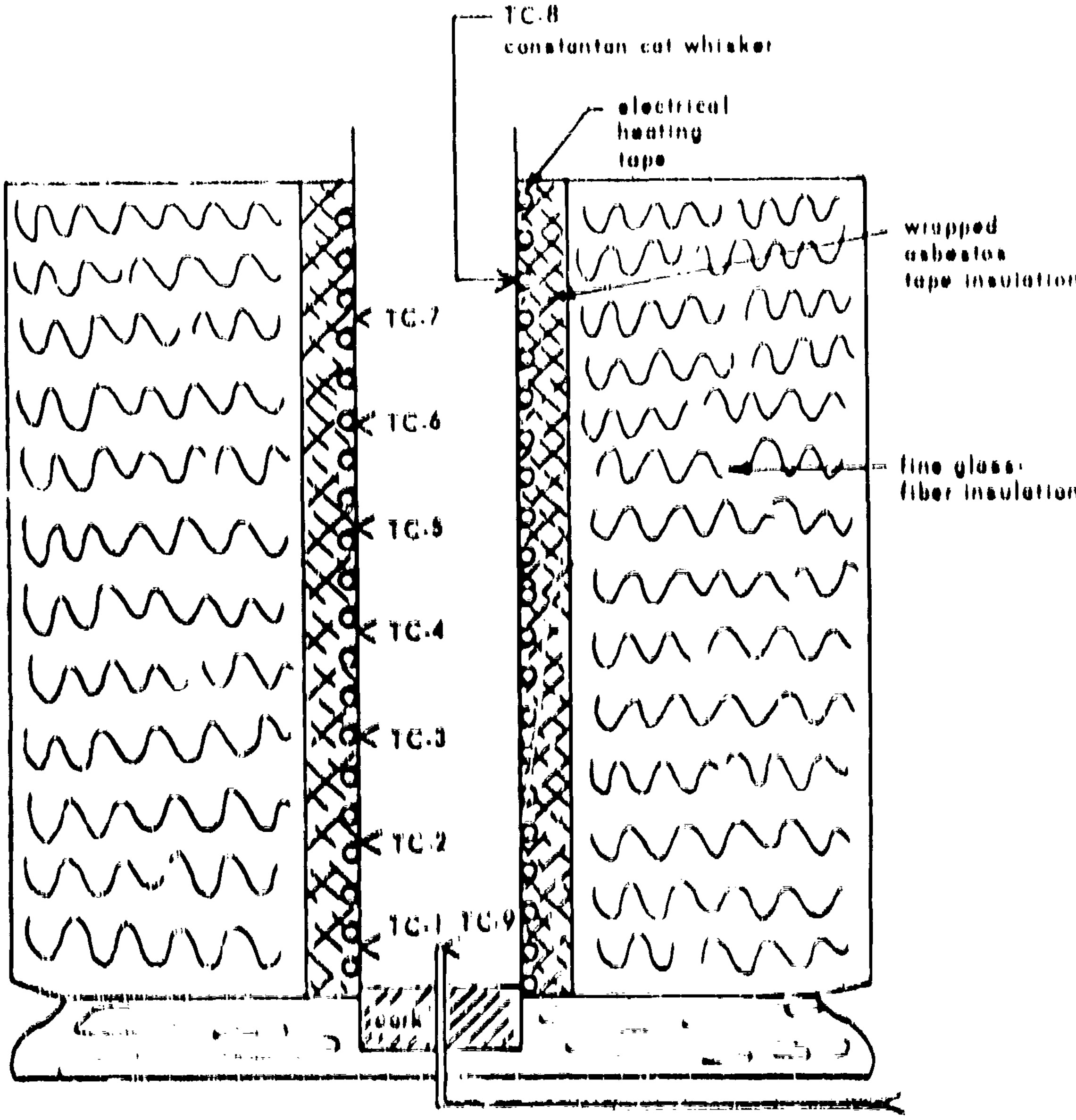

Figure 18. Schematic of small tube experiment.

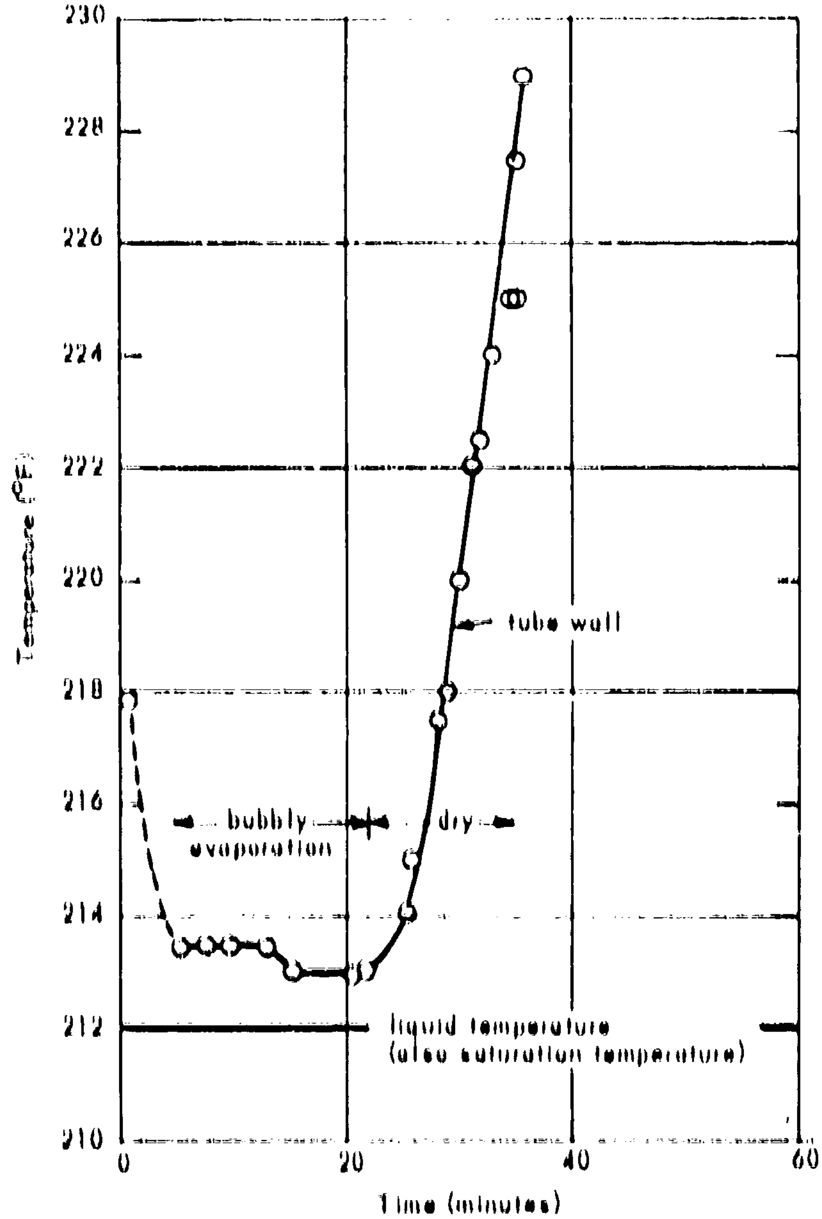

Figure 19. Time-temperature trace for small tube experiment at a constant heat input of 4,100 Btu/ft², hr.

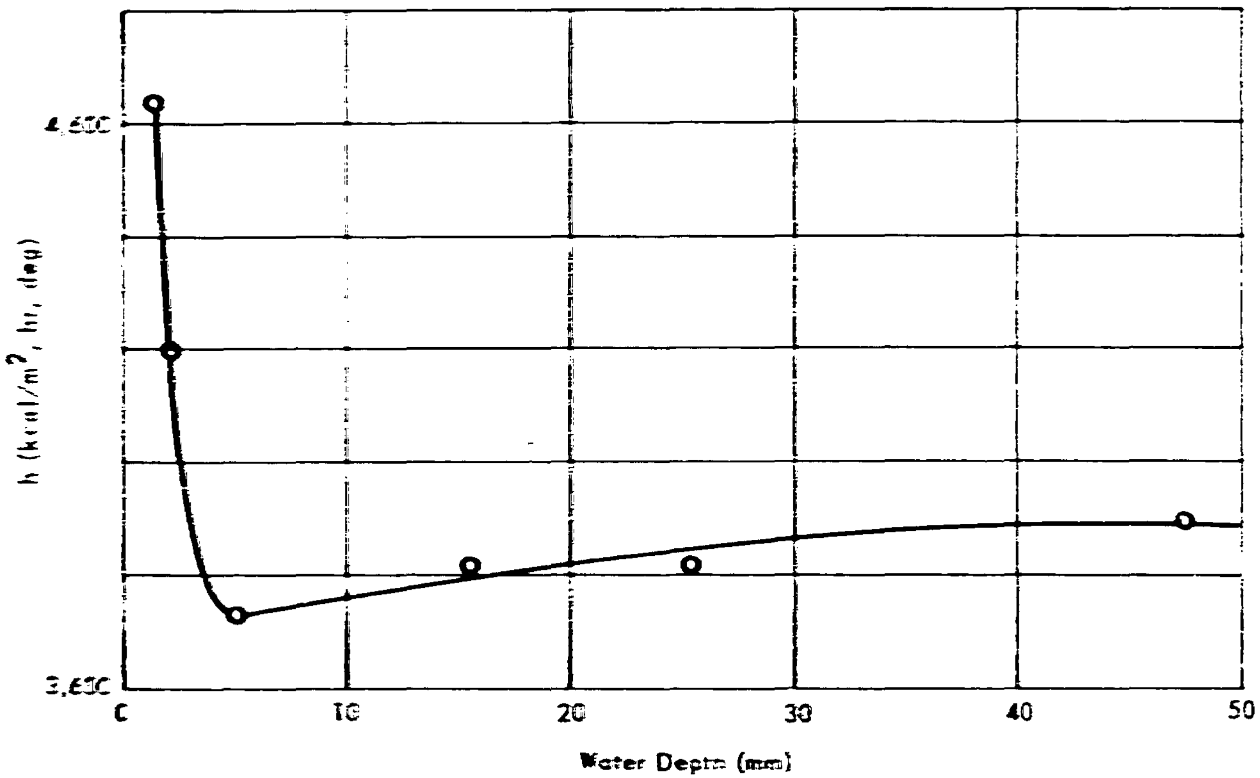

Figure 20. Effect of coolant depth on boiling film coefficient at constant Q/A. (From Jacob and Linke, 1935, as reported by Kutateladze, 1952.)

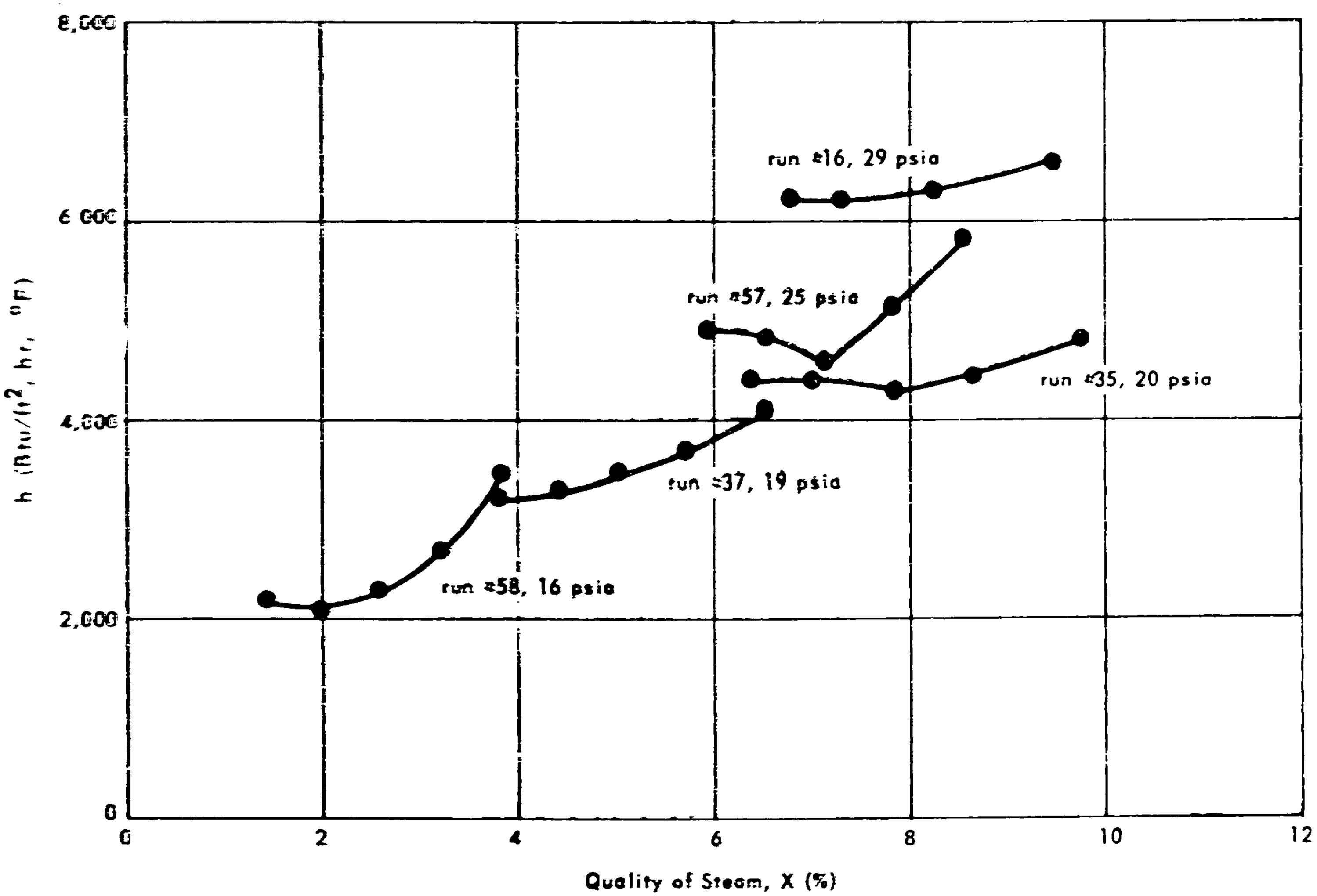

Figure 21. Heat transfer to wet steam at varying pressures. (From data by Sani, 1960.)

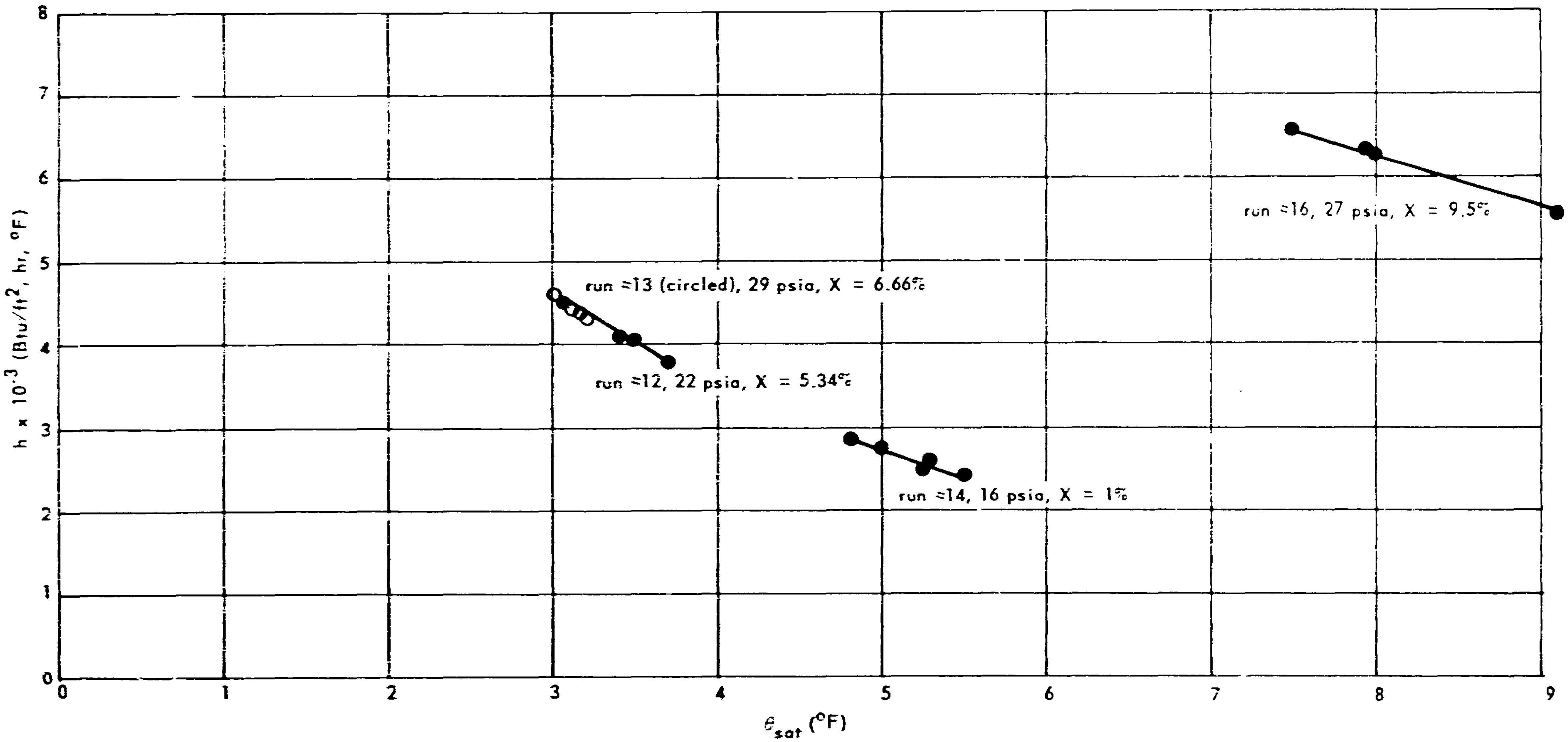

Figure 22. Heat transfer to wet steam plotted against wall-to-saturation-temperature difference. (From data by Sani, 1960.)

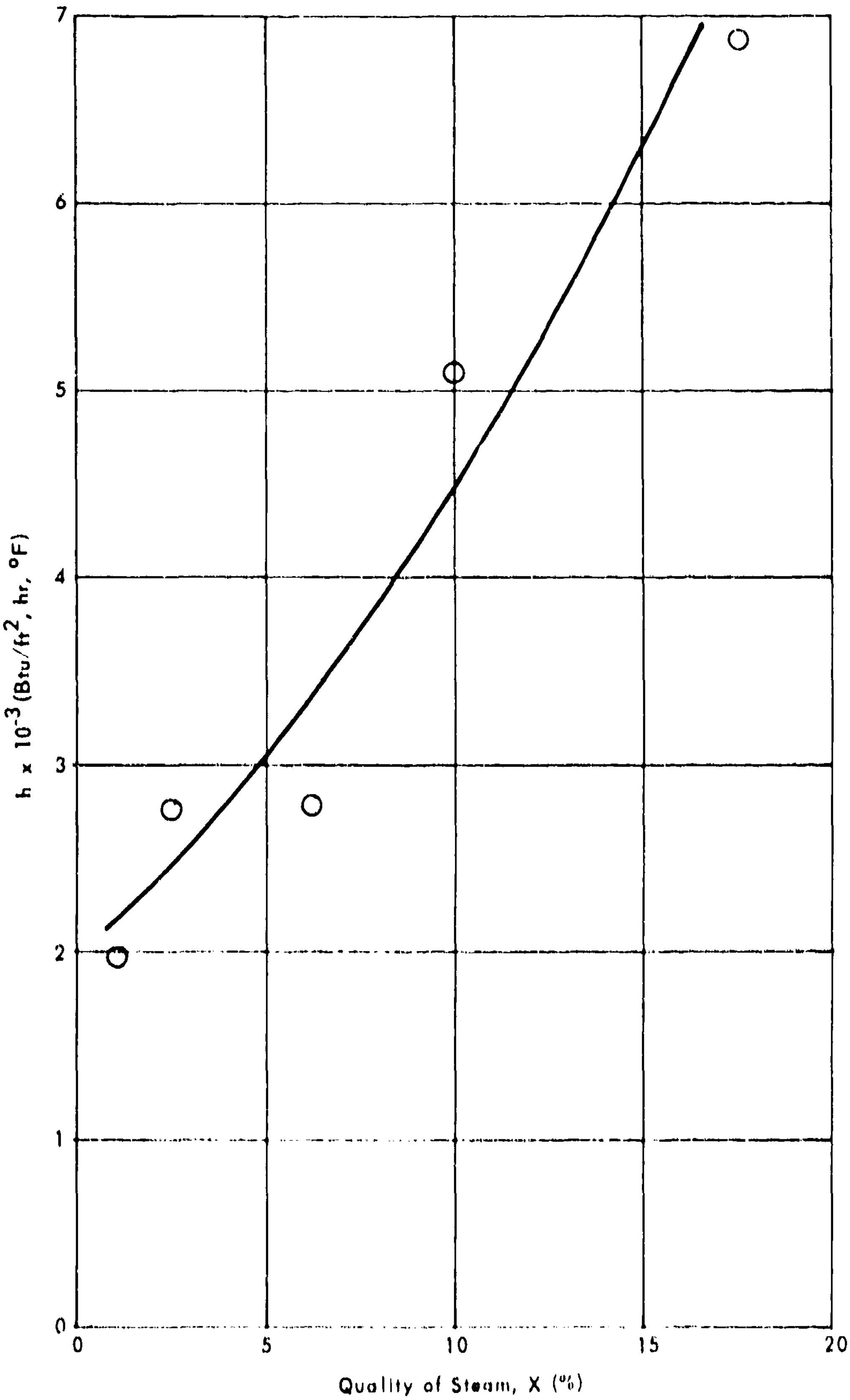

Figure 23. Heat transfer to wet steam plotted against quality of steam flowing. (After data by Dengler and Addoms, 1956.)

Appendix

PLANNED EXPERIMENT

The continuing experimental investigation will consist of testing and modifying a single-tube bench model of the evaporating portion of a vapor-compression still, using thin-film evaporation instead of boiling, and various methods of liquid deposition to sustain the evaporating thin film. Aspects of the study will include spray techniques for dispersing the brine in the dry saturated steam to produce a suitable mixture; an investigation of possible scaling problems; and experiments to determine the limits of steam quality, brine concentrations, and temperatures which may be useful in full-scale equipment. Attempts will be made to obtain or develop a suitable mathematical model to describe the heat transfer in terms of flow, steam quality, etc. Failing this, the best possible empirical correlation of the data will be made.

The equipment is largely constructed. Figure A-1 shows a schematic cross section of the experimental model. The brine spray nozzle is not shown, but would be in the circuit ahead of the wet steam inlet. The double copper wall is designed to provide a radiation environment for the test tubing approximately like that which would be found in a multitube process exchanger. Thermocouples installed in the tube walls are imbedded as shown in Figure A-2.

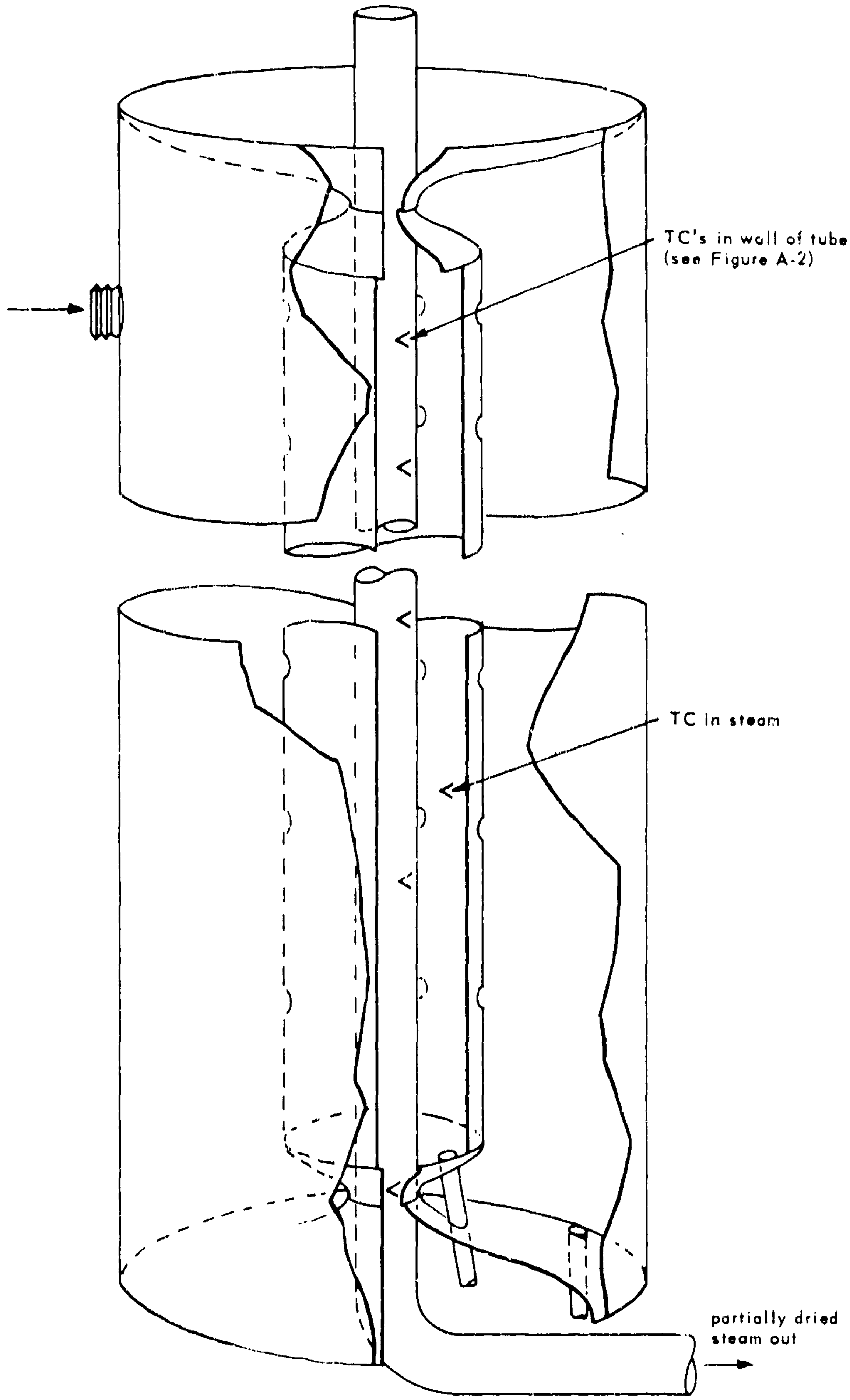

Figure A-1. Schematic drawing of single-tube experiment for demonstrating thin-film fluid evaporation.

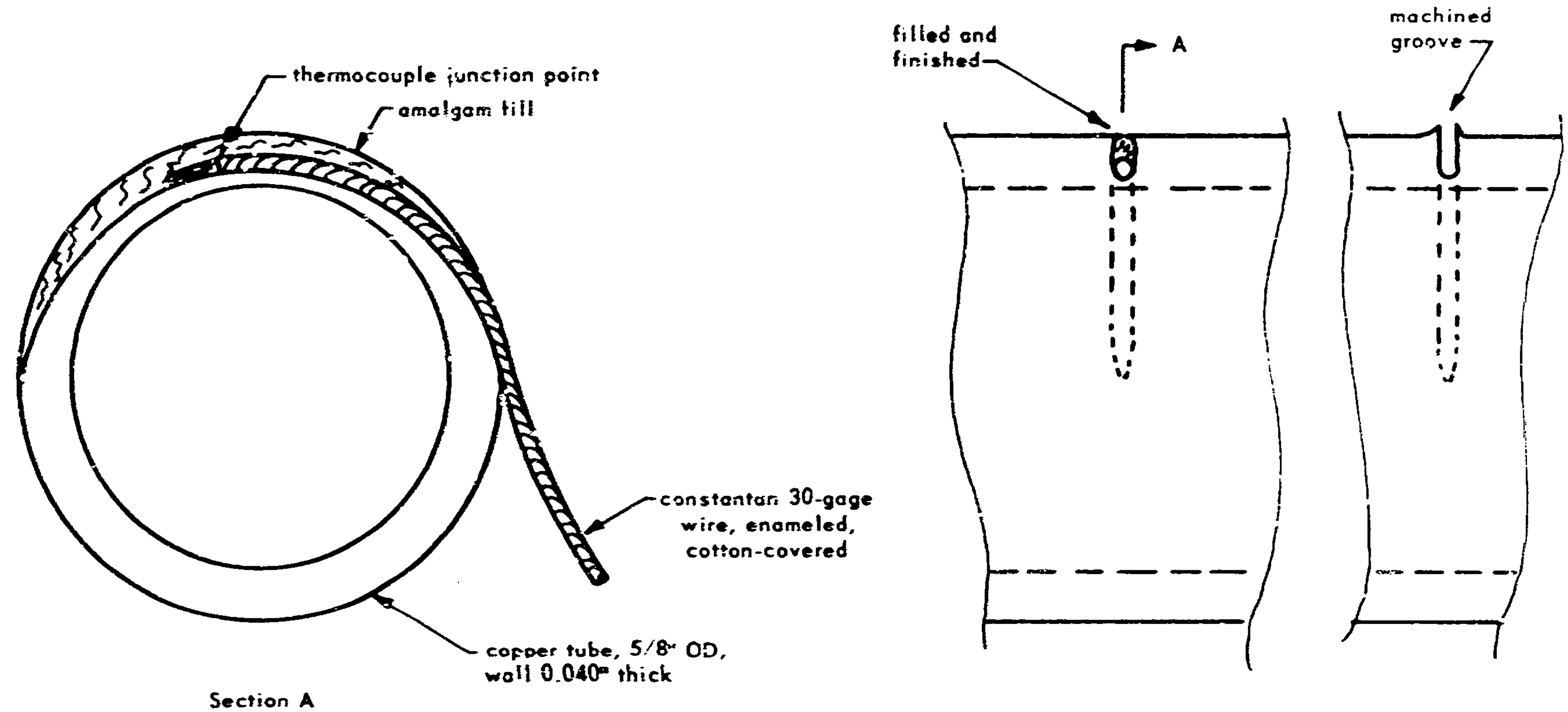

Figure A-2. Method of installing thermocouples in tube wall of single-tube experiment.

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The concept of evaporation from a very thin film without boiling is considered in detail, and two small experiments are reported. It is shown, both theoretically and experimentally, that very high evaporation rates can be obtained with the very thin film technique; methods of maintaining a thin film continuously in a practical vapor-compression still are considered. A single-tube experiment, in which methods of introducing feed water and checking probable scaling problems will be studied, is described as the next phase of this task.

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